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REVIEW: 25 years of Sea Level Records from the Arctic Ocean Using Radar Altimetry

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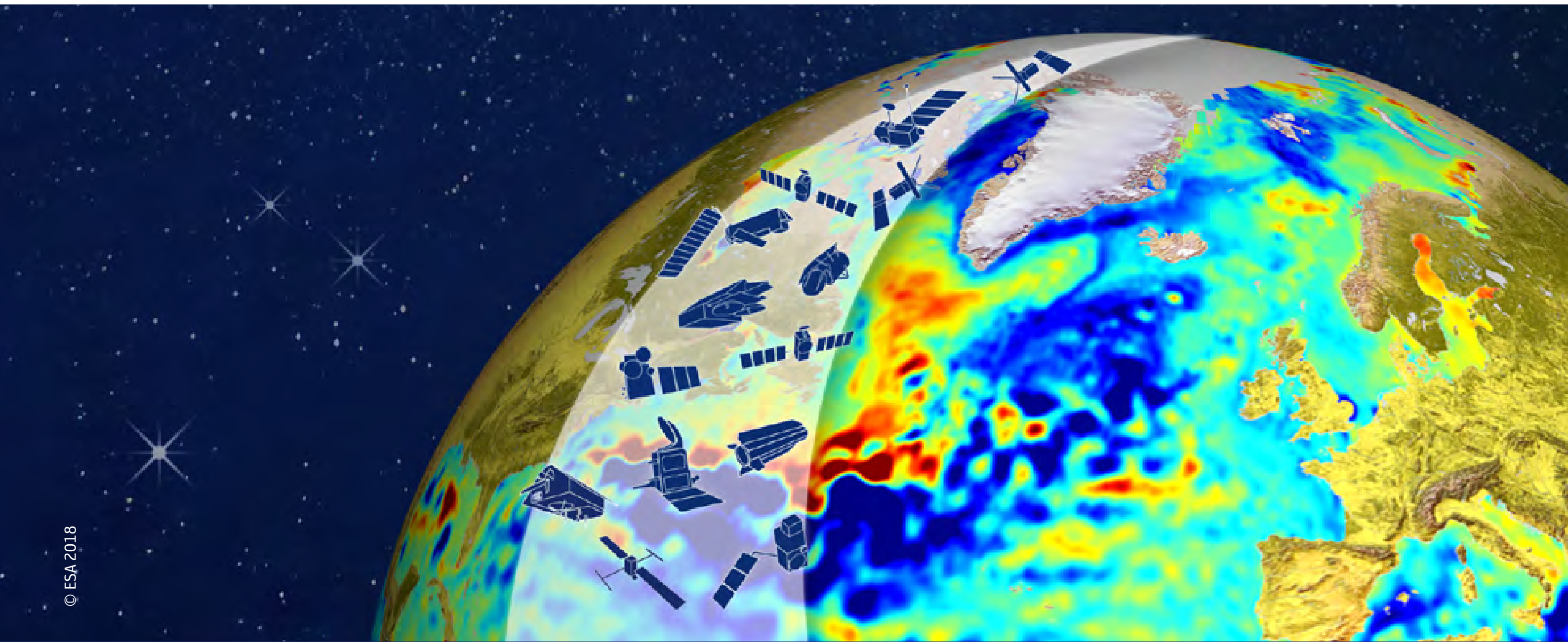
→ 25 YEARS OF PROGRESS IN RADAR ALTIMETRY SYMPOSIUM



ABSTRACT BOOK

24–29 September 2018 | Ponta Delgada, São Miguel Island
Azores Archipelago, Portugal

ABSTRACT BOOK

25 Years of Progress in Radar Altimetry Workshop

24-29 September 2018

Ponta Delgada

Azores

Last update: 19 October 2018

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3. Programme

25 YEARS OF PROGRESS IN RADAR ALTIMETRY PROGRAMME | **DAY 1 | MONDAY 24 SEPTEMBER 2018**

8:00 - 8:55 | Registration

8:55 - 13:00 | Plenary Opening Session Chairs: ***Jérôme Benveniste, ESA - Pascal Bonnefond, Observatoire de Paris, SYRTE***

08:55 - 09:00	Introduction and Scope of the Symposium	Jérôme Benveniste	ESA	
09:00 - 09:10	Welcome ESA	Maurice Borgeaud	ESA	
09:10 - 09:20	Welcome CNES	Juliette Lambin	CNES	FR
09:20 - 09:30	Address from the Portuguese Government	Manuel Heitor	Minister of Science, Technology and Higher Education	PT
09:30 - 09:40	Welcome from the Azores Government	Vasco Cordeiro	President of Azores Regional Government	PT

	Title	Presenter		
09:40 - 10:00	Keynote: Early Development of Satellite Altimetry	Byron Tapley	University of Texas at Austin	USA
	Byron Tapley[1] | [1]University of Texas at Austin, Austin, TX, United States			
10:00 - 10:20	Keynote: Legacy Achievements of the First 25 Years of the TOPEX/Poseidon and Jason Series	Eric Leuliette	NOAA	USA
	Eric Leuliette[1], Pascal Bonnefond[2], Remko Scharroo[3], Josh Willis[4] | 1NOAA Lab. for Satellite Altimetry, College Park, United States, [2]Observatoire de Paris-SYRTE, Paris, France, [3]EUMETSAT, Darmstad, Germany, [4]Jet Propulsion Laboratory, Pasadena, United States			
10:20 - 10:30	Keynote: Assessment of the Global Mean Sea Level Budget over the Altimetry Era: an International Initiative	Anny Cazenave	LEGOS ISSI	FR
	Anny Cazenave[1],[2], Benoit Meyssignac[1], The WCRP Global Sea Level Budget Group | [1]LEGOS, Toulouse, France, [2]ISSI, Bern, Switzerland			
10:30 - 10:40	Keynote: A 25-Year Record of Global Mean Sea Level Change: What Have We Learned?	Steven Nerem	University of Colorado	USA
	Robert Steven Nerem[1], Anny Cazenave[2] | [1]University Of Colorado, Boulder, United States, [2]LEGOS, Observatoire Midi-Pyrénées, Toulouse, France			
10:40 - 11:00	Keynote: Global Ocean Circulation from Satellite Altimetry: Progress and Future Challenges	Lee-Lueng Fu	JPL	USA
	Lee-Lueng Fu[1] | [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, United States			
11:00 - 11:20	Keynote: Satellite Altimetry and the Copernicus Marine Service: Status and Perspectives	Pierre-Yves Le Traon	Mercator Ocean	FR
	Pierre-Yves Le Traon[1] | [1]Mercator Ocean, Ramonville st Agne, France			

	Title	Presenter		
11:20 - 11:40	Keynote: Progresses of Altimetry for Marine Ecology: from a Dataset for Biophysical Studies, to a Tool for Conservation Policies	Francesco D'Ovidio	LOCEAN-IPSL	FR
	Francesco d'Ovidio[1], Yoav Lehahn[2], Cédric Cotté[3], Marina Lévy[1], Christophe Guinet[4], Philippe Koubbi[5] | [1]CNRS LOCEAN-IPSL, Paris, France, [2]Dep. of Marine Geosciences, Univ. of Haifa, Haifa, Israel, [3]National Museum of Natural History, LOCEAN-IPSL, Paris, France, [4]CNRS - CEBC, Chizé, France, [5]Sorbonne Universités, UPMC, Paris, France			
11:40 - 11:50	Keynote: The Ocean Mean Dynamic Topography: 25 Years of Improvements	Marie-Hélène Rio	CLS	FR
	Marie-Helene Rio[1], San ine Mulet[1], Gerald Dibarboure[2], Nicolas Picot[2] | [1]CLS, Ramonville Saint Agne, France, [2]CNES, Toulouse, France			
11:50 - 12:00	Keynote: Twenty-Five Years of Progress in Sea Floor Mapping by Satellite Altimetry	Walter Smith	NOAA	USA
	Walter Smith[1], David Sandwell[2], Karen Marks[1], Ole Andersen[3] | [1]Noaa Laboratory For Satellite Altimetry, College Park, United States, [2]Scripps Institution of Oceanography, La Jolla , United States, [3]Danish Space Center, Copenhagen, Denmark			
12:00 - 12:20	Keynote Coastal Altimetry: Assimilating Altimeter Observations in a High-Resolution Shelf-Seas Model – The Met Office 1.5km European North-West Shelf Forecasting	Robert King	Met Office	UK
	Robert King[1], Matthew Martin[1], James While[1] | [1]UK Met Office, Exeter, United Kingdom			
12:20 - 12:40	Keynote: CryoSat-2 for Inland Water Applications – Potential, Challenges and Future Prospects	Cécile Kittel	Technical University of Denmark	DK
	Cecile M. M. Kittel[1], Liguang Jiang[1], Raphael Schneider[1,3], Ole Baltazar Andersen[2], Karina Nielsen[2], Peter Bauer-Gottwein[1] | [1]Department of Environmental Engineering, Technical University Of Denmark, Kgs. Lyngby, Denmark, [2]National Space Institute, Technical University of Denmark, Kgs. Lyngby, Denmark, [3]Geological Survey of Denmark and Greenland, Copenhagen, Denmark			
12:40 - 12:50	Keynote: Polar Altimetry	Duncan Wingham	NERC	UK
	Andrew Shepherd[1], Duncan Wingham[2], Alan Muir[2], Andy Ridout[2], Lin Gilbert[2], Mal McMillan[1], Rachel Tilling[1], Hannes Konrad[1], Tom Slater[1], Ines Otosaka[1], Anna Hogg[1], Noel Gourmelen[3] | [1]CPOM, Leeds, United Kingdom, [2]NERC, Swindon, United Kingdom, [3]CPOM, London, United Kingdom, [4]University of Edinburgh, Edinburgh, UK			
12:50 - 13:00	Keynote: The Younger, Thinner, Faster Arctic Sea Ice Cover: Tracking Change over Fifteen Years	Sinead Louise Farrell	University of Maryland / ESSIC NOAA	USA
	Sinead Louise Farrell[1,2], Jennifer Hutchings[3], Kyle Duncan[1,2], Joshua McCurry[1,2] | [1]University of Maryland / ESSIC, College Park, United States, [2]NOAA Laboratory for Satellite Altimetry, College Park, United States, [3]Oregon State University / CEOAS, Corvallis, United States			

13:00 - 14:30 **Lunch**

14:30 - 16:10 | Parallel Sessions

AUDITORIUM **Open Ocean #1: Large-Scale Ocean Circulation and Sea-Level Session | Chairs: Eric Leuliette (NOAA) - Jacques Verron (IGE)**

	Title	Presenter		
14:30 - 14:50	Keynote: Global Sea Level Budget Assessment: Preliminary Results From ESA's CCI Sea Level Budget Closure Project	Anny Cazenave	LEGOS	FR
	Martin Horwath[1], Anny Cazenave[2], Hindumathi Kulaiappan Palanisamy[2], Ben Marzeion[3], Frank Paul[4], Raymond Le Bris[4], Anna Hogg[5], Inès Otosaka[5], An ew Shepherd[5], Petra Döll[6], Denise Caceres[6], Hannes Müller Schmied[6], Johnny A. Johannessen[7], Jan Even Øie Nilsen[7], Roshin P. Raj[7], René Forsberg[8], Louise Sandberg Sørensen[8], Valentina R. Barletta[8], Per Knudsen[8], Ole Baltazar Andersen[8], Heidi Villadsen[8], Christopher John Merchant[9], Claire Rachel Macintosh[9], Christopher Old[9], Karina von Schuckmann[10], Benjamin Gutknecht[1], Kristin Novotny[1], An eas Groh[1], Jérôme Benveniste[11] | [1]Technische Universität Dresden, Dresden, Germany, [2]LEGOS, Toulouse, France, [3]University of Bremen, Germany, [4]University of Zurich, Switzerland, [5]University of Leeds, UK, [6]Goethe University Frankfurt, , Germany, [7]Nansen Environmental and Remote Sensing Center, Bergen, Norway, [8]DTU Space, Lyngby, Denmark, [9]University of Reading, UK, [10]Mercator Ocean, Toulouse, France, [11]ESA ESRIN, Frascati, Italy			
14:50 - 15:10	Keynote: Causes of Sea-Level Variability: Oceanic Chaos Versus Atmospheric Forcing	Thierry Penduff	CNRS - IGE	FR
	Thierry Penduff[1], Sally Close[1], Stéphanie Leroux[2,1], Ixetl Garcia-Gomez[1], Guillaume Sérazin[3,1], Jean-Marc Molines[1], Bernard Barnier[1], Laurent Bessières[4], Laurent Terray[4] | [1]IGE - MEOM, Grenoble, France, [2]Ocean Next, Grenoble, France, [3]LEGOS, Toulouse, France, [4]CERFACS - CECI, Toulouse, France			
15:10 - 15:30	Has the Gulf Stream Slowed Down during 1993-2016?	Shenfu Dong	AOML	USA
	Shenfu Dong[1], Molly Baringer[1], Gustavo Goni[1] | [1]AOML, National Oceanic and Atmospheric Administration, Miami, United States			
15:30 - 15:50	Revisited Sea Level Budget over 2005-2015 Indicates Large Deep Ocean Warming and Large Earth Energy Imbalance	Benoit Meyssignac	LEGOS	FR
	Benoit Meyssignac[1], Alejandro Blazquez[1], Alexandre Couhert[2], Lionel Zawadski[3], Flavien Mercier[2], Michael Ablain[3], Anny Cazenave[1] | [1]LEGOS, Toulouse, France, [2]CNES, Toulouse, France, [3]CLS, Toulouse, France			
15:50 - 16:10	Impact of Recent ENSO Variability on Global and Regional Sea Level	Benjamin Hamlington	Old Dominion University	USA
	Benjamin Hamlington[1], JT Reager[2], Robert Leben[3] Old Dominion University, Norfolk, United States, [2]NASA JPL, Pasadena, USA, [3]University of Colorado, Boulder, USA			

16:10 - 16:40 **Coffee Break**

LAGOA DAS 7 CIDADES Land Processes and Inland Water #1: Lakes and Reservoirs

Chairs: Charon Birkett (ESSIC, University of Maryland) - Alexei Kouraev (LEGOS) - Angelica Tarpanelli (IRPI-CNR)

	Title	Presenter		
14:30 - 14:50	Keynote: Aral Sea Evolution from Satellite Altimetry and other Remote Sensing Data	Jean-Francois Cretaux	CNES-LEGOS	FR
	Jean-francois Cretaux[1], Muriel Berge-Nguyen[1] | [1]CNES-LEGOS, Toulouse, France			
14:50 - 15:10	Contribution of 25 Years of Satellite Radar Altimetry Towards Enhancing the Great Lakes Operational Forecasting System	C.K. Shum	The Ohio State University Chinese Academy of Sciences	USA
	Yuanyuan Jia[1], C.K. Shum[1,2], Philip Chu[3], Yi Chao[4], Ehsan Forootan[5], Pengfei Xue[6], Ting-Yi Yang[1], Xiaobin Cai[2], Chungyen Kuo[7], Jian Sun[1] | [1]Division of Geodetic Science, School of Earth Sciences, The Ohio State University, Columbus, USA, [2]Insitute of Geodesy & Geophysics, Chinese Academy of Sciences, Wuhan, China, [3]NOAA Great Lakes Environmental Research Laboratory (GLERL), Ann Arbor, USA, [4]Remote Sensing Solutions, Monrovia, USA, [5]School of Earth and Ocean Science, Cardiff University, Cardiff, UK, [6]Great Lakes Research Center, Michigan Technological University, Houghton, USA, [7]Department of Geomatics, National Cheng Kung University, Tainan, Taiwan			
15:10 - 15:30	15-years Surface Water Storage Changes of Lakes and Reservoirs in Poyang Lake Basin Based on Multi-Spectral Imageries and Multi-Mission Radar Altimetry	C.K. Shum	The Ohio State University Chinese Academy of Sciences	CN
	Xiaobin Cai[1,2], C.K Shum[2,1], Yuanyuan Jia[2], Tingyi Yang[2] | [1]Institute Of Geodesy And Geophysics,Chinese Academy of Sciences, wuhan, China, [2]Division of Geodetic Science, School of Earth Sciences, Ohio State University, Columbus, U.S.A			
15:30 - 15:50	Estimating 3-D Reservoir Bathymetry from Multi-Satellite Data	Augusto Getirana	NASA	USA
	Augusto Getirana1, Hahn Jung[1] | [1]NASA Goddard Space Flight Center, Greenbelt, United States			
15:50 - 16:10	Lake Storage Variation on the Endorheic Tibetan Plateau and its Attribution to Climate Change since the New Millennium	Jida Wang	Kansas State University	USA
	Fangfang Yao[1], Jida Wang[1], Kehan Yang[2], Chao Wang[3], Blake Walter[1], Jean-François Crétaux[4] | [1]Kansas State University, Manhattan, United States, [2]University of Colorado Boulder, Boulder, United States, [3]University of Puerto Rico, San Juan, United States, [4]Centre National d'Études Spatiales , Toulouse, France			
16:10 - 16:40	**Coffee Break**			

LOGOA DO COGRO Cryosphere #1: Ice Sheet, Glaciers, Ice Cap

Chairs: Jérôme Bouffard (ESA) | Sara Fleury (LEGOS)

	Title	Presenter		
14:30 - 14:50	Review: Understanding Drivers of Change in Antarctica's Ice Shelves from 25 years of Continuous Satellite Radar Altimetry	Matthew Siegfried	Stanford University	USA
	Helen Amanda Fricker[1], Susheel Adusumilli[1], Fernando Paolo[2], Laurie Padman[3], Matthew Siegfried[4] | [1]Scripps Institution of Oceanography/UCSD, [2]Jet Propulsion Laboratory, [3]Earth & Space Research, [4]Stanford University			
14:50 - 15:10	Net Retreat of Antarctic Grounding Lines Detected by CryoSat-2 Radar Altimetry	Thomas Slater	Alfred Wegener Institute	DE
	Hannes Konrad[1], Andrew Shepherd[2], Lin Gilbert[3], Anna Hogg[2], Malcolm McMillan[2], Alan Muir[3], Thomas Slater[2] | [1]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, [2]Centre for Polar Observation and Modelling, University of Leeds, Leeds, United Kingdom, [3]Centre for Polar Observation and Modelling, University College London, London, United Kingdom			
15:10 - 15:30	A Reconciled Estimate of Antarctic Peninsula Mass Balance	Anna Hogg	CPOM	UK
	Anna Hogg[1], An ew Shepherd[1], Kate Briggs[1], Lin Gilbert[2], Alan Muir[2], Martin Horwath[4], Thomas Nagler[3], Jan Wuite[3], Malcolm McMillan[1], Noel Gourmelen[5], Helmut Rott[3] | [1]CPOM, Leeds, United Kingdom, [2]CPOM, London, United Kingdom, [3]ENVEO, Innsbruck, Austria, [4]Technical University of esden, esden, Germany, [5]University of Edinburgh, Edinburgh, United Kingdom			
15:30 - 15:50	Dual Frequency Radar Altimetry - Measuring Greenland Firn Properties from Space	Sebatian B. Simonsen	DTU Space	DK
	Sebatian B. Simonsen[1], Louise Sandberg Sørensen[1], Lars Stenseng[2], Rene Forsberg[1] | [1]Department Of Geodynamics, Dtu Space, Technical University Of Denmark, Kgs. Lyngby, Denmark, [2]Department of Geodesy, DTU Space, Technical University of Denmark, Kgs. Lyngby, Denmark			

	Title	Presenter		
15:50 - 16:10	Contribution of Satellite Radar Altimetry Towards Quantifying Present-Day Mass Balance Estimates for Mountain Glaciers and Ice Caps	C.K. Shum	The Ohio State University Chinese Academy of Sciences	USA CN

C.K. Shum[1,9], Yuanyuan Jia[1], Vibhor Agarwal[1], Jian Sun[1], Kung Shang[1], Junyi Guo[1], Yuchan Yi[1], Santiago de La Pena[1], Ian Howat[2], Chungyen Kuo[7], Hyongki Lee[8], Zhiyue Sun[8], Qiang Shen[9], Guoqing Zhang[3], Alexander Braun[4], Graham Cogley[5], Xiaoli Ding[6], Xiaoli Su[10] | [1]School of Earth Sciences, The Ohio State University, Columbus, United States, [2]Byrd Polar & Climate Research Center, Ohio State University, Columbus, United States, [3]Instittue of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, [4]Department of Geological Sciences & Geological Engineering, Queen's University, Kingston, Canada, [5]Department of Geography, Trent University, Peterborough, Canada, [6]Department of Land Survey & Geo-Informatics, Hong Kong Polytechnic University, Kowloon, Hong Kong, [7]Department of Geomatics, National Cheng Kung University, Tainan, Taiwan, [8]Department of Civil & Environmental Engineering, University of Houston, Houston, United States, [9]Institute of Geodesy & Geophyscis, Chinese Academy of Sciences, Wuhan, China, [10]Hauzhong University of Science & Techology, Wuhan, China

16:10 - 16:40	**Coffee Break**

16:40 - 18:20 | Parallel Sessions

AUDITORIUM Open Ocean #2: Tides, Internal Tides, Internal Waves | Chairs: Florent Lyard (LEGOS) - Richard Ray (NASA)

	Title	Presenter		
16:40 - 17:00	Review: Progress and Challenges of the Tide Correction for Altimetry over Last 25 Years	Florent Lyard	LEGOS-CNRS	FR

Florent Lyard[1], Loren Carrère[2], Mathilde Cancet[3], Jean-Michel Lemoine[4], Christian Bizouard[5], Pascal Gegout[6] | [1]LEGOS-CNRS, Toulouse, France, [2]CLS, Toulouse, France, [3]Noveltis, Toulouse, France, [4]GET, Toulouse, France, [5]IERS/Observatoire de Paris, Paris, France, [6]GET, Toulouse

17:00 - 17:20	Keynote: Internal Tides: the View from Satellite Altimetry	Richard Ray	NASA	USA

Richard Ray[1], Edward Zaron[2], Gary Egbert[3] | [1]NASA Goddard Space Flight Center, Greenbelt, United States, [2]Portland State University, Portland, United States, [3]Oregon State University, Corvallis, United States

	Title	Presenter		
17:20 - 17:40	Review: A Review of Global Internal Tide and Wave Modeling	Brian K. Arbic	University of Michigan	USA
	Brian K. Arbic[1], Matthew H. Alford[2], Joseph K. Ansong[1,3], Maarten C. Buijsman[4], J. Thomas Farrar[5], Conrad A. Luecke[1], Dimitris Menemenlis[6], Arin D. Nelson[1], Hans E. Ngodock[7], James G. Richman[8], Anna C. Savage[1,2], Jay F. Shriver[7], Innocent Souopgui[4], Patrick G. Timko[1,9], Alan W. Wallcraft[8], Luis Zamudio[8], Zhongxiang Zhao[10] | [1]University of Michigan, United States, [2]UC San Diego,United States, [3]University of Ghana, Ghana, [4]University of Southern Mississippi, United States, [5]Woods Hole Oceanographic Institution, United States, [6]NASA JPL, United States, [7]NRL Stennis Space Center, United States, [8]Florida State University, United States, [9]Welsh Local Centre, United Kingdom, [10]Applied Physics Laboratory, United States			
17:40 - 18:00	Review: A Review of New Internal-Tides Models and Validation Results	Loren Carrere	CLS	FR
	Loren Carrere[1], Florent Lyard[2], Romain Baghi[1], Nicolas Picot[3], Brian Arbic[4], Brian Dushaw[5], Gary Egbert[6], Svetlana Erofeeva[6], Richard Ray[7], Clément Ubelmann[1], Edward Zaron[8], Zhongxiang Zhao[9], Maarten Buijsman[10], James Richman[11], Jay Schriver[12] | [1]CLS, Ramonville-saint-agne, France, [2]LEGOS-CNRS, Toulouse, France, [3]CNES, Toulouse, France, [4]University of Michigan, United States, [5]NERSC, Norway, [6]Oregon State University, United States [7]NASA Goddard, Greenbelt, United States, [8]Portland State University, United States, [9]University of Washington, Seattle, United States, [10]U-Southern Mississippi, United States, [11]Florida State University, United States, [12]Naval Research Laboratory, United States			
18:20 - 19:30	**Icebreaker**			

LAGOA DAS 7 CIDADES Land Processes and Inland Water #2: Methods and Rivers

Chairs: Charon Birkett (ESSIC, University of Maryland) - Jean-François Crétaux (LEGOS) - Augusto Getirana (NASA-GSFC)

	Title	Presenter		
16:40 - 17:00	Benefits of the Open Loop Tracking Command (OLTC) : Extending Conventional Nadir Altimetry to Inland Water Monitoring	Sophie Le Gac	CNES	FR
	Sophie Le Gac[1], François Boy[1], Nicolas Picot[1] | [1]CNES, Toulouse, France			
17:00 - 17:20	Implications of Specular Echoes for Monitoring of Inland Water Bodies	Ron Abileah	jOmegak	USA
	Ron Abileah[1], Stefano Vignudelli[2], Andrea Scozzari[3] | [1]jOmegak, San Carlos, United States, [2]Consiglio Nazionale delle Ricerche (CNR-IBF), Pisa, Italy, [3]Consiglio Nazionale delle Ricerche (CNR-ISTI), Pisa, Italy			
17:20 - 17:40	Improvements Brought by Updated Water Masks onto Altimetric Measurements over Rivers	Pierre Fabry	Along-Track	USA
	Pierre Fabry[1], Moein Zohary[1], Nicolas Bercher[1], Marco Restano[2], Américo Ambrozio[3], Jérôme Benvéniste[4] | [1]Along-Track S.A.S., Plougonvelin, France, [2]SERCO, Frascati, Italy, [3]DEIMOS, Italy, [4]ESA-ESRIN, Frascati, Italy			
17:40 - 18:00	Multi-Mission Based River Levels	Karina Nielsen	DTU Space	DK
	Karina Nielsen[1], Elena Zakharova[2], Ole Baltazar Andersen[1], Lars Stenseng[1], Per Knudsen[1] | [1]DTU Space, Kgs. Lyngby, Denmark, [2]LEGOS, Toulouse, France			
18:00 - 18:20	Evaluating Multiple-Mission Satellite Altimetry Towards Establishing a Long-term Climate Record of Poorly–Gauged Rivers in Indonesian Borneo	Yohuanes Budi Sulistioadi	Mulawarman University	IDN
	Yohanes Budi Sulistioadi[1,4], Ting-yi Yang[2], Yuanyuan Jia[2], Dedy Cahyadi[3], C.K. Shum[2] | [1]Center of Geo-spatial Information Infrastructure Development (CGIID/PPIIG), Mulawarman University, Samarinda, Indonesia, [2]Division of Geodetic Science, School of Earth Sciences, The Ohio State University, Columbus, United States of America, [3]Faculty of Computer Science and Information Technology, Mulawarman University, Samarinda, Indonesia, [4]Faculty of Forestry, Mulawarman University, Samarinda, Indonesia			
18:20 - 19:30	**Icebreaker**			

LOGOA DO COGRO Cryosphere #2: Sea Ice and Polar Oceanography

Chairs: Jérôme Bouffard (ESA) | Sara Fleury (LEGOS)

	Title	Presenter		
16:40 - 17:00	Review: 15 Year Climate Data Record of Arctic Sea Ice Thickness from Two Generations of Satellite Radar Altimeters	Stefan Hendricks	Alfred-Wegener-Institut	DE
	Stefan Hendricks[1], Stephan Paul[1], Robert Ricker[1], Eero Rinne[2] | [1]Alfred-Wegener-Institut, Helmholtz Zentrum für Polar Und Meeresforschung, Bremerhaven, Germany, [2]Finnish Meteorological Institute, Helsinki, Finland			
17:00 - 17:20	Arctic Sea Ice Floe Size and Thickness Distributions from Multi-decadal Satellite Radar Altimeter Measurements	Rachel Tillig	CPOM - University Of Leeds	UK
	Rachel Tilling[1], Andy Ridout[2], An ew Shepherd[1] | [1]CPOM - University Of Leeds, Leeds, United Kingdom, [2]CPOM - University College London, London, United Kingdom			
17:20 - 17:40	Arctic Icebergs Climatology 1992-Present from Altimeter Data	Jean Tournadre	Ifremer	FR
	Jean Tournadre[1], Rozenn Gourves-Cousin[1] | [1]Ifremer, Plouzané, France			
17:40 - 18:00	Sea level and Ocean Circulation in the Ice-Covered Polar Oceans: Variability, Change and Implications for Climate	Thomas Armitage	JPL	USA
	Thomas Armitage[1], Ron Kwok[1], Sheldon Bacon[2], Andrew Thompson[3], Alek Petty[4], Glenn Cunningham[1], Andy Ridout[5] | [1]JPL, Pasadena, United States, [2]National Oceanography Center, Southampton, United Kingdom, [3]California Institute of Technology, Pasadena, United States, [4]NASA Goddard Space Flight Center, Greenbelt, United States, [5]Centre for Polar Observation and Modelling, UK			
18:00 - 18:20	Exploring the Synergy of Sea Surface Height, Ocean Bottom Pressure, and Sea Surface Salinity to Study Arctic Ocean Freshwater Changes	Severine Fournier	JPL	USA
	Severine Fournier[1], Tony Lee[1], Xiaochun Wang[2], Ron Kwok[1] | [1]JPL, Pasadena, United States, [2]University of California at Los Angeles, Los Angeles, United States			
18:20 - 19:30	**Icebreaker**			

8:30 - 8:50 | Parallel Sessions

AUDITORIUM **Open Ocean #3: Mesoscale–Smaller-Scale Currents | Chairs: Rosemary Morrow (LEGOS) - Bo Qiu (University of Hawaii)**

	Title	Presenter		
8:30 - 8:50	Review: How Our Understanding of Ocean Mesoscale Eddies Has Evolved over 25 Years	Rosemary Morrow	LEGOS-OMP	FR
	Rosemary Morrow[1], Lee-Lueng Fu[2], J. Thomas Farrar[3], Hyodae Seo[3], Pierre-Yves Le Traon[4] | [1]LEGOS-OMP, Toulouse, France, [2]JPL-NASA, Pasadena, United States, [3]Woods Hole Oceanographic Institute, Woods Hole, United States, [4]Mercator-Ocean, Ramonville-St-Agne, France			
8:50 - 9:10	Review: A Review of 30 Years of Advances in Rossby Wave Theory Prompted by Satellite Altimetry	Remi Tailleux	University of Reading	UK
	Remi Tailleux[1] | [1]University of Reading, Reading, United Kingdom			
9:10 - 9:30	Review: Overview of Fine-scale Multiplatform Experiments in the Southwest Mediterranean Sea: Lessons Learnt in the Last Five Years	Ananda Pascual	IMEDEA (CSIC-UIB)	ES
	Ananda Pascual[1], Simón Ruiz[1], Antonio Sánchez-Román[1], Laura Gómez-Navarro[1,2], Bàrbara Barceló-Llull[1], Lara Díaz-Barroso[1], Pierre Chabert[1], Eugenio Cutolo[3], Mara Amelia Freilich[4], Emma Heslop[3], Benjamin Casas[1], Marc Torner[3], Baptiste Mourre[3], Eva Alou[3], Yuri Cotroneo[7], Giuseppe Aulicino, Evan Mason[1], Amala Mahadevan[4], Joaquin Tintore[1,3], Francesco D'Ovidio[5], Ronan Fablet[6], John Allen[3] | [1]IMEDEA(CSIC-UIB), Esporles, Spain, [2]IGE, Grenoble, France, [3]SOCIB, Palma, Spain, [4]WHOI, Woods Hole, United States, [5]LOCEAN, Paris, France, [6]IMT Atlantique, Brest, France, [7]Università degli Studi di Napoli "Parthenope", Napoli, Italy			
9:30 - 9:50	Decadal Mesoscale Eddy Modulations in the Western North Pacific Subtropical Gyre	Bo Qiu	University Of Hawaii	USA
	Bo Qiu[1], Shuiming Chen[1] | [1]University Of Hawaii At Manoa, Honolulu, United States			
9:50 - 10:10	Characterizing the Transition From Balanced to Unbalanced Motions in the Southern California Current System	Teresa Chereskin	Scripps Institution of Oceanography	USA
	Teresa Chereskin[1], Sarah Gille[1], Cesar Rocha[1], Dimitris Menemenlis[2] | [1]Scripps Institution of Oceanography, La Jolla, United States, [2]NASA Jet Propulsion Laboratory, Pasadena, United States			
10:10 - 10:40	**Coffee Break**			

LAGOA DAS 7 CIDADES **Land Processes and Inland Water #3: Rivers (cont'd), Welands and Soil Moisture**

Chairs: Jean-François Crétaux (LEGOS) - Alexei Kouraev (LEGOS) - Karina Nielsen (DTU Space)

	Title	Presenter		
8:30 - 8:50	The Yukon River in Alaska and the Great Ruaha River in Tanzania: Assessing River and Wetland Dynamics to Aid Ground-Based Monitoring Networks and Ecological Restoration Projects within Complex and Diverse River Basins.	Charon Birkett	University of Maryland	USA
	Charon Birkett[1], David Bjerklie[2], Eric Wolanski[3], Mr. Emilian Kihwele[4] | [1]University Of Maryland, College Park, United States, [2]USGS Water Resources Division, East Hartford, USA, [3]TropWATER/CMES James Cook University, Townsville, Australia, [4]TANAPA, Serengeti National Park, Tanzania			
8:50 - 9:10	Channel Storage Change: a New Remote Sensed Surface Water Measurement	Steve Coss	Ohio State University	USA
	Steve Coss[1], Michael Durand[1], Yuchan Yi[1], Qi Guo[1], C.K. Shum[1], George Allen[2], Xiao Yang[3], Tamlin Pavelsky[3] | [1]Ohio State University, Columbus, United States, [2]NASA Jet Propulsion Laboratories, Pasadina, United States, [3]University of North Carolina, Chaple Hill, United States			
9:10 - 9:30	Potential of the Radar Altimetry for Estimation of the River Input to the Arctic Ocean	Elena Zakharova	Institute of Water Problems	RU
	Elena Zakharova[1], Karina Nielsen[2], Inna Krylenko[1], Alexei Kouraev[3] | [1]Institute of Water Problems, Moscow, Russia, [2]DTU SPACE, Lyngby, Denmark, [3]LEGOS, Toulouse, France			
9:30 - 9:50	Multi-Mission Satellite Remote Sensing for River Discharge Estimation: Recent Advances and Future Directions	Angelica Tarpanelli	IRPI-CNR	IT
	Angelica Tarpanelli[1], Luca Brocca[1], Stefania Camici[1], Silvia Barbetta[1], Christian Massari[1], Paolo Filippucci[1], Tommaso Moramarco[1] | [1]IRPI-CNR, Perugia, Italy			
9:50 - 10:10	Soil Moisture from Satellite Radar Altimetry - from ERS-2 to Sentinel-3	Philippa Berry	Roch Remote Sensing	UK
	Philippa Berry[1], Jerome Benveniste[2] | [1]Roch Remote Sensing, Roch, Haverfordwest, United Kingdom, [2]ESA-ESRIN, Frascati, Italy			
10:10 - 10:40	**Coffee Break**			

LOGOA DO COGRO Altimetric Contributions to Gravity Field, Marine Geodesy, Bathymetry Modeling

Chairs: Sean Bruinsma (CNES) - Marie-Hélène Rio (CLS)

	Title	Presenter		
8:30 - 8:50	Keynote: Marine Gravity Field Mapping from Altimetry – Advancement with 2nd Generation Altimeters	Ole Baltazar Andersen	DTU Space	DK
	Ole Baltazar Andersen[1], Per Knudsen[1], David Sandwell[2], Walter Smith[3], David McAdoo[3], Karen Marks[3] | [1]DTU Space, Kongens Lyngby, Denmark, [2]Scripps Institution of Oceanography, San Diego, United States, [3]NOAA, Washington, United States			
8:50 - 9:10	The Coastal Mean Dynamic Topography in Norway Observed by CryoSat-2 and GOCE	Vegard Ophaug	NMBU	NO
	Vegard Ophaug[1], Martina Idzanovic[1], Ole Baltazar Andersen[2] | [1]Faculty of Science and Technology (RealTek), Norwegian University of Life Sciences (NMBU), Ås, Norway, [2]DTU Space, Technical University of Denmark, Lyngby, Denmark			
9:10 - 9:20	Opportunities and Challenges of Satellite Altimeter Gravity over Lakes	Kirsten Fletcher	Getech	UK
	Chris Green[1],[2], Kirsten Fletcher[1], Sam Cheyney[1],[3], Simon Campbell[1] | [1]Getech, Leeds, United Kingdom, [2]School of Earth and Environment, University of Leeds, Leeds, United Kingdom, [3]School of Environmental Sciences, University of Hull, Hull, United Kingdom			

LOGOA DO COGRO Precise Orbit Determination

Chairs: Alexandre Couhert (CNES) - Michiel Otten (ESA)

	Title	Presenter		
9:20 - 9:40	Future Challenges for POD	Space Agency Groups (CNES, NASA and ESA)		
9:40 - 9:42	REAPER Re-Scoped: Updated Orbit Solutions for the Full ERS-1 and ERS-2 Mission Periods	Pieter Visser	Delft University of Technology	NL
	Pieter Visser[1], Michiel Otten[2] | [1]Delft University Of Technology, Delft, The Netherlands, [2]PosiTim UG, Seeheim-Jugenheim, Germany			
9:42 - 9:44	Reprocessing of TOPEX/Poseidon Precise Orbits in the CNES GDR-F Standards	Clément Masson	CS SI	FR
	Eva Jalabert[2], Clément Masson[1], Alexandre Couhert[2], John Moyard[2], Flavien Mercier[2] | [1]CS SI, Toulouse, France, [2]CNES, Toulouse, France			

9:44-9:46	First Orbit Determination Results for Sentinel-3B	Peter Heike	Positim UG	DE
	Pierre Féménias[3], Jaime Fernández[2], Peter Heike[1] | [1]Positim UG, Seeheim-Jugenheim, Germany, [2]GMV AD, Tres Cantos, Spain, [3]ESA-ESRIN, Frascati, Italy			
9:46-9:48	Improved GNSS Phase Maps in Flight Modelling and Identification, Application on Jason-2 and Jason-3	Hanane Ait Lakbir	CS SI	FR
	Hanane Ait Lakbir[1], F Mercier[2], A Couhert[2] | [1]CS SI, Toulouse, France, [2]CNES, Toulouse, France			
9:48 - 9:50	Generating Precise and Homogeneous Orbits for ESA's Altimetry Missions: ERS-1, ERS-2, Envisat, Cryosat-2, and Sentinel-3A	Michiel Otten	ESA	DE
	Michiel Otten[1], C Flohrer[1], T Springer[1], W Enderle[1] | [1]ESA-ESOC, Darmstadt, Germany			
9:50 - 9:52	Latest Results From the Geomed2 Project: Geoid and the DOT in the Mediterranean Area	Sean Bruinsma	CNES	FR
	Sean Bruinsma[1], Riccardo Barzaghi[2], Geomed[2] Team | [1]CNES, Toulouse, France, [2]Politecnico di Milano, Milan, Italy			
9:52 - 9:54	Jason-3 and Sentinel-3A GPS Processing Using Zero-Difference Integer Ambiguity Fixing	Flavien Mercier	CNES	FR
	Flavien Mercier[1], Hanane Ait-Lakbir[1], Clément Masson[1], Alexandre Couhert[1] | [1]CNES, Toulouse, France			
9:54 - 9:56	The Geomed2 Combined Geoid Model	Sean Bruinsma	CNES	FR
	Sean Bruinsma[1], George Vergos[2], Franck Reinquin[1], Ilias Tziavos[2], Riccardo Barzaghi[3], Daniela Carrion[3], Sylvain Bonvalot[4], Lucia Seoane[4], Marie-Françoise Lequentrec-Lalancette[5], Corinne Salaun[5], Per Knudsen[6], Ole Andersen[6], Marie-Helene Rio[7] | [1]CNES, Toulouse, France [2]Aristotle University of Thessaloniki, Thessaloniki, Greece, [3]Politecnico di Milano, Milan, Italy, [4]GET UMR 5563, Toulouse, France, [5]SHOM, Brest, France, [6]DTU Space, Kopenhagen, Denmark, [7]CLS, Ramonville Saint Agne, France			
9:56 - 9:58	Orbit Validation of Sentinel-3 Mission	Jaime Fernández	GMV AD	ES
	Pierre Féménias[3], Jaime Fernández[2], Heike Peter[1], Copernicus POD QWG team | [1]Positim UG, Swisttal, Germany, [2]GMV AD, Tres Cantos, Spain, [3]ESA-ESRIN, Frascati, Italy			
9:58 - 10:00	Precise Orbit Determination of the Sentinel Satellites with Gipsy-Oasis	Wim Simons	Delft University Of Technology	NL
	Wim Simons[1], Pieter Visser[1], Marc Naeije[1], Copernicus POD QWG team | [1]Delft University of Technology, Delft, The Netherlands			
10:10 - 10:40	**Coffee Break**			
10:40 - 12:20	**25 Years Progress in Radar Altimetry & IDS Poster Session**			
12:20 - 14:00	**Lunch Break**			

14:30 - 16:10 | Parallel Sessions

AUDITORIUM **25-Year Altimetric Record #1: Building the Climate Record: Accuracy and Precision over 25 Years of Altimetry Data**

Chairs: Michael Ablain (CLS) - Frank Lemoine (NASA/GSFC) - Josh Willis (NASA/JPL)

	Title	Presenter		
14:00 - 14:20	Review: Evolution of LRM and SAR Altimeter Ocean Data Processing towards Improved Performances	Thomas Moreau	CLS	FR
	Thomas Moreau[1], Pierre Thibaut[1], Laiba Amarouche[1], Jeremie Aublanc[1], Fanny Piras[1], Jean-christophe Poisson[1], Pierre Rieu[1], François Boy[2], Alejan o Bohe[2], Nicolas Picot[2], Franck Borde[3], Constantin Mavrocordatos[3], Alejan o Egido[4], Walter H. F. Smith[4] | [1]CLS, Ramonville St Agne, France, [2]CNES, Toulouse, France, [3]ESA, Noordwijk, The The Netherlands, [4]NOAA, College Park, United States			
14:20 - 14:40	oward an Overview of CryoSat Data Quality over the Ice and the Ocean	Jerome Bouffard	ESA	IT
	Jérôme Bouffard[1], Tommaso Parrinello[1], Pierre Féménias[1] | [1]ESA- ESRIN, Frascati, Italy			
14:40 - 15:00	DUACS Multi-Mission Sea Level Products: Continuous Improvements for the Past 20 Years	Yannice Faugere	CLS	FR
	Yannice Faugere[1], Isabelle Pujol[1], Ubelmann Clement[1], Antoine Delepoulle[1], Maxime Ballarotta[1], Guillaume Taburet[1], Gerald Dibarboure[2], Nicolas Picot[2] [1]CLS, Ramonville, France, [2]CNES, Toulouse, France			
15:00 - 15:20	Lessons Learned From 25 years of Cross Calibration of the Altimetry Missions Over Ocean	Sylvie Labroue	CLS	FR
	Sylvie Labroue[1], Michael Ablain[1], Joel Dorandeu[1], Annabelle Ollivier[1], Sabine Philipps[1], Matthias Raynal[1], Hélène Roinard[1], Nicolas Picot[2] | [1]CLS, Ramonville St Agne, France, [2]CNES, Toulouse, France			
15:20 - 15:40	In Situ Calibration and Validation of Satellite Altimetry: A Review of 25 Years of Ongoing Monitoring	Christopher Watson	University Of Tasmania	AU
	Christopher Watson[1], Pascal Bonnefond[2], Bruce Haines[3], Stelios Mertikas[4] | [1]University Of Tasmania, Hobart, Australia, [2]Observatoire de Paris - SYRTE, Paris, France, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, United States, [4]Technical University of Crete, Chania, Greece			
15:40 - 16:10	**Coffee Break**			

LAGOA DAS 7 CIDADES Synergy Between Altimetry, Other Data and Models in Support of Operational Oceanography #1

Chairs: Joël Dorandeu (CLS) - Clara Lázaro (University of Porto) - Gregory Smith (Environment and Climate Change Canada)

	Title	Presenter		
14:00 - 14:20	Improved Global Surface Currents from the Merging of Altimetry and Sea Surface Temperature Data	Marie-Helene Rio	CLS	FR
	Marie-Helene Rio[1], Rosalia Santoleri[2], Daniele Ciani[2], Gerald Dibarboure[3], Nicolas Picot[3], Craig Donlon[4] | [1]CLS, Ramonville Saint Agne, France, [2]ISAC-CNR, Rome, Italy, [3]CNES, Toulouse, France, [4]ESTEC, Nordwijk, The Netherlands			
14:20 - 14:40	Implementation of a Balance Operator in a Multi-Scale Data Assimilation System for Operational Forecasting	Joseph D'Addezio	University of Southern Mississippi	USA
	Joseph D'Addezio[1], Innocent Souopgui[2], Max Yaremchuk[3], Gregg Jacobs[3], Scott Smith[3], Robert Helber[3], Clark Rowley[3] | [1]University of Southern Mississippi, Hattiesburg, United States, [2]University of New Orleans, New Orleans, United States, [3]Naval Research Laboratory, Stennis Space Center, United States			
14:40 - 15:00	Mapping Ocean Mesoscales with a Combined Doppler Scatterometer and Altimeters Constellation	Clement Ubelmann	CLS	FR
	Clement Ubelmann[1], Marie-Hélène Rio[1], Fabrice Ardhuin[3], Gerald Dibarboure[2] | [1]CLS, Ramonville, France, [2]CNES, Toulouse, France, [3]IFREMER, Brest , France			
15:00 - 15:20	Estimating of Any Altimeter Mean Seal Level (MSL) ifts between 1993 and 2017 by Comparison with Tide-Gauges Measurements	Michaël Ablain	CLS	FR
	Michaël Ablain[1], Rémi Jugier[1], Nicolas Picot[2] | [1]CNES, Ramonville Saint-Agne, France, [2]CNES, Toulouse, France			
15:20 - 15:40	Impact of Altimetry Observations in the Real Time Ocean Monitoring Systems: GODAE OceanView Observing System Evaluation Studies	Elisabeth Remy	Mercator Ocean	FR
	Elisabeth Remy[1], Yosuke Fujii[2], T GODAE OceanView OSEval Task | [1]Mercator Ocean, Ramonville Saint Agne, France, [2]Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan			
15:40 - 16:10	**Coffee Break**			

LOGOA DO COGRO **Advances in our Understanding of Coastal Processes #1**

Chairs: Luciana Fenoglio-Marc (University of Bonn) - Stefano Vignudelli (CNR-IBF)

	Title	Presenter		
14:00 - 14:20	From the Open Ocean to the Coast and Back With ALES: Bypassing Waveform Tail Artefacts to Observe the Coastal Sea Level Variability	Marcello Passaro	DGFI-TUM	DE
	Marcello Passaro[1], Paolo Cipollini[2], Graham D Quartly[3], Walter H F Smith[4], Denise Dettmering[1], Christian Schwatke[1] | [1]Deutsches Geodätisches Forschungsinstitut Der Technischen Universität München (DGFI-TUM), München, Germany, [2]Telespazio VEGA UK for ESA Climate Office ECSAT, Didcot, United Kingdom, [3]Plymouth Marine Laboratory, Plymouth, United Kingdom, [4]National Oceanic and Atmospheric Administration, Silver Spring, United States			
14:20 - 14:40	Sentinel-3 SAR Altimetry over Coastal and Open Ocean: Assessment of Improved Retrieval Methods from the ESA SCOOP Project	David Cotton	Satellite Oceanographic Consultants	UK
	David Cotton[1], Thomas Moreau[2], Matthias Raynal[2], Eduard Makhoul[3], Mathilde Cancet[4], Luciana Fenoglio-Marc[5], Marc Naeije[6], M Joana Fernandes[7], Clara Lazaro[7], An ew Shaw[8], Paolo Cipollini[12], Marco Restano[9], Américo Ambròsio[10], Jérôme Benveniste[11] | [1]Satellite Oceanographic Consultants, Stockport, United Kingdom, [2]CLS, Ramonville Saint-Agne, France, [3]isardSAT, Guildford, UK, [4]Noveltis, Labège, France, [5]University of Bonn, Bonn, Germany, [6]Delft University of Technology, Delft, The The Netherlands, [7]University of Porto, Porto, Portugal, [8]SKYMAT, Southampton, UK, [9]SERCO-ESA, Frascati, Italy, [10]DEIMOS-ESA, Frascati, Italy, [11]ESA-ESRIN, Frascati, Italy, [12]Telespazio VEGA-ECSAT, Harwell, UK			
14:40 - 15:00	SAMOSA++: A New Coastal SAR Altimetry Retracker and Its Application in German Bight and West Baltic Sea	Salvatore Dinardo	He Space	DE
	Salvatore Dinardo[1], Luciana Fenoglio[2], Christopher Buchhaupt[3], Remko Scharroo[4], M. Joana Fernandes[5], Jerome Benveniste[6], Matthias Becker[3] | [1]He Space, Franckfurt, Germany, [2]TU Bonn-Institute for Geodesy and Geoinformation , Bonn, Germany, [3]TU Darmstadt-Institute for Geodesy , Darmstadt, Germany, [4]EUMETSAT, Darmstadt, Germany, [5]University of Porto, Faculty of Science, Porto, Portugal, [6]ESA-ESRIN, Frascati, Italy			
15:00 - 15:20	Validation of Improved Significant Wave Heights from the Brown-Peaky Rretracker around East Coast of Australia	Fukai Peng	The University of Newcastle	AU
	Fukai Peng[1], Xiaoli Deng[1] | [1]The University Of Newcastle, Australia, Jesmond, Australia			
15:20 - 15:40	Synergy between In-situ and Altimetry Data to Observe and Study the Fine-Scale Dynamics in the Ligurian Sea (NW Mediterranean Sea)	Alice Carret	LEGOS-OMP	FR
	Alice Carret[1], Florence Birol[1], Claude Estournel[2] | [1]LEGOS-OMP, Toulouse, France, [2]LA-OMP, Toulouse, France			
15:40 - 16:10	**Coffee Break**			

16:10 - 18:20 | Parallel Sessions

AUDITORIUM 25-Year Altimetric Record #2: Global Mean Sea Level as a Key Climate Indicator

Chairs: Michael Ablain (CLS) - Frank Lemoine (NASA/GSFC) - Josh Willis (NASA/JPL)

	Title	Presenter		
16:10 - 16:30	Keynote: Improvements in Accurately Measuring Sea Level Change from Space and Expectations for the Future: an ESA Climate Change Initiative	Michaël Ablain	CLS	FR
	Michaël Ablain[1], Anny Cazenave[2], Benoît Meyssignac[2], Jean-François Legeais[1], Jérôme Benveniste[3] | [1]CLS, Ramonville Saint-Agne, France, [2]LEGOS, Toulouse, France, [3]ESA- ESRIN, Frascati, Italy			
16:30 - 16:50	Sea Level Rise as Measured by 11 Satellite Radar Altimeters	Remko Scharroo	EUMETSAT	DE
	Remko Scharroo[1], Eric Leuliette[2], Amanda Plagge[2,3] | [1]EUMETSAT, Darmstadt, Germany, [2]NOAA Lab. for Satellite Altimetry, College Park, USA, [3]GST Inc., Greenbelt, USA			
16:50 - 17:10	A Review of the Global Sea Level Record Construction with 25 Years of Reference Missions	Benoit Legresy	CSIRO	AU
	Benoit Legresy[1], Christopher Watson[2], John Church[3] | [1]CSIRO Climate Science Centre, Hobart, Australia, [2]University of Tasmania, Hobart, Australia, [3]University of New South Whales, Sydney, Australia			
17:10 - 17:30	Acceleration and Long Term Rise in Global Sea Level: A TOPEX Perspective	Josh Willis	JPL	USA
	Josh Willis[1], Philip Callahan[1], Shailen Desai[1], Nicolas Picot[2], Helene Roinard[3], Jean-Damien Desjonqueres[1], Matthieu Talpe[1], Thierry Guinle[2], Glenn Shirtliffe[1] | [1]NASA Jet Propulsion Laboratory, Los Angeles, United States, [2]Centre Nationale des Etudes Spatial, Toulouse, France, [3]Collecte Localisation Satellites, Ramonville, France			
17:30 - 17:50	Searching for Acceleration in Regional Sea Level Measurements	Benjamin Hamlington	Old Dominion University	USA
	Benjamin Hamlington[1], Robert Nerem[2], John Fasullo[3], Brian Beckley[4] | [1]Old Dominion University, Norfolk, United States, [2]University of Colorado, Boulder, United States, [3]NCAR, Boulder, USA, [4]NASA GSFC, Greenbelt, United States			

LAGOA DAS 7 CIDADES Synergy Between Altimetry, Other Data and Models in Support of Operational Oceanography #2

Chairs: Joël Dorandeu (CLS) - Clara Lázaro (University of Porto) - Gregory Smith (Environment and Climate Change Canada)

	Title	Presenter		
16:10 - 16:30	Combination of AVISO/DUACS and Argo Data Sets to Follow the Evolution of Long Lived Eddies and their 3D Structure from 2000 to 2015 in the Mediterranean Sea.	Alex Stegner	CNRS, Ecole Polytechnique	FR
	Alex Stegner[1], Briac LeVu[1], Cori Pegliasco[2], Alexis Chaigneau[2], Artemis Ioannou[1], Franck Dumas[3], Yannice Faugere[4], Xavier Carton[5] | [1]LMD, CNRS, Ecole Polytechnique, Palaiseau, France, [2]LEGOS, CNRS, Toulouse, France, [3]SHOM, Brest, France, [4]CLS, Toulouse, France, [5]LOPS, UBO, IUEM, Brest, France			
16:30 - 16:50	Influence of North Atlantic Teleconnection Patterns on Sea Level Anomaly of the North Atlantic Ocean and Seas around Europe	Clara Lázaro	University Of Porto, Faculty Of Sciences	PT
	Clara Lázaro[1,2], Nieves Lorenzo[3], Joana Fernandes[1,2], Luisa Bastos[1,2], Isabel Iglesias[2] | [1]Universidade do Porto, Faculdade de Ciências, Porto, Portugal, [2]Centro Interdisciplinar de Investigação Marinha e Ambiental (CIIMAR), Universidade do Porto, Matosinhos, PORTUGAL, [3]Environmental Physics Laboratory, Facultad de Ciencias, Universidade de Vigo, Ourense, Spain			
16:50 - 17:10	Summary of Results from CASSIS Project: Southwestern Atlantic Currents From In-Situ and Satellite Altimetry	Martin Saraceno	University Of Buenos Aires CIMA/CONICET-UBA UMI-IFAECI/CNRS-CONICET-UBA	AR
	Martin Saraceno[1,2,3], Guillermina Paniagua[1,2,3], Loreley Lago[2,3,4], Camila Artana[6], Ramiro Ferrari[1,2,3], Alberto Piola[2,3,5], Christine Provost[6], Raul Guerrero[4] | [1]University of Buenos Aires, Ciudad Autonoma de Buenos Aires, Argentina, [2]CIMA/CONICET-UBA, Buenos Aires, Argentina, [3]UMI-IFAECI/CNRS-CONICET-UBA, Buenos Aires, Argentina, [4]INIDEP, Mar del Plata, Argentina, [5]Servicio de Hidrografía Naval, Buenos Aires, Argentina, [6]LOCEAN/UMR 7159, Paris, France			
17:10 - 17:30	Transport Efficiency of an Agulhas Ring from Combined Satellite Altimetry and Argo iles	Francesco Nencioli	Plymouth Marine Laboratory	UK
	Francesco Nencioli[1], Giorgio Dall'Olmo[1], Graham Quartly[1] | [1]Plymouth Marine Laboratory, Plymouth, United Kingdom			
17:30 - 17:50	Radar Altimeters for Enhanced Polar Ocean Observations	Michel Tsamados	University College London	UK
	Tiago Dotto[2], Michel Tsamados[1], Harry Heorton[1], Andrew Ridout[1], Isobel Lawrence[1], Sheldon Bacon[2], Alberto Naveiro-Garabato[3] | [1]University College London, London, United Kingdom, [2]National Oceanography Centre Southampton, Southampton, UK, [3]Universtity of Southampton, Southampton, UK, [4]NASA JPL, United States			

LOGOA DO COGRO — Advances in our Understanding of Coastal Processes #2

Chairs: Mathilde Cancet (NOVELTIS) - Marcello Passaro (TUM)

	Title	Presenter		
16:10 - 16:30	Coastal Sea Level Trends	Luciana Fenoglio	University of Bonn	DE
	Luciana Fenoglio[1], Salvatore Dinardo[2], Bern Uebbing[1], Joanna Staneva[6], Remko Scharroo[2], Joana Fernandes[5], Jerome Benveniste[3], Christopher Buchhaupt[4], Matthias Becker[4], Jürgen Kusche[1] | [1]University Of Bonn, Bonn, Germany, [2]EUMETSAT, Darmstadt, Germany, [3]ESA/ESRIN, Frascati, Germany, [4]Technical University Darmstadt, Darmstadt, Germany, [5]University of Porto, Porto, Portugal, [6]Institute of Coastal Research , Geesthacht, Germany			
16:30 - 16:50	Under-Estimated Wave Contribution to Coastal Sea Level Change and Rise	Angelique Melet	Mercator Ocean	FR
	Angelique Melet[1], Benoit Meyssignac[2], Rafael Almar[2], Gonéri Le Cozannet[3] | 1Mercator Ocean, Ramonville Saint Agne, France, [2]LEGOS, Université de Toulouse, CNES, CNRS, IRD, UPS, Toulouse, France, [3]BRGM / French Geological Survey, Orléans, France			
16:50 - 17:10	Seamless Geoids across Coastal Zones: Comparison of Satellite and Airborne Gravity across the Seven Continents – and an Azores Heritage Case	Rene Forsberg	DTU Space	DK
	Rene Forsberg[1], Arne Olesen[1], Daniel Barnes[2], Sarah Ingalls[2], Clifton Minter[2], Manny Presicci[2] | [1]DTU Space, Lyngby, Denmark, [2]National Geospatial-Intelligence Agency, Arnold, USA			
17:10 - 17:30	The Impact of Satellite Altimeter Observations on Estimates of Cross-Shelf Fluxes in the Mid-Atlantic Bight	Andrew Moore	University of California Santa Cruz	USA
	Andrew Moore[1], John Wilkin[2], Julia Levin[2], Hernan Arango[2] | [1]University Of California Santa Cruz, Santa Cruz, United States, [2]Rutgers University, New Brunswick, United States			
17:30 - 17:50	Can Ocean Temperature Changes Around the Greenland Ice Sheet Be Inferred With Altimetry	Ian Fenty	JPL	USA
	Ian Fenty[1], Robert Nerem[2] | [1]NASA Jet Propulsion Laboratory, Pasadena, United States, [2]Cooperative Institute for Research in Environmental Sciences/U. of Colorado, Boulder, Boulder, USA			

8:30 - 10:10 | Parallel Sessions

AUDITORIUM 25-Year Altimetric Record #3: Ongoing Scientific and Technical Challenges

Chairs: Michael Ablain (CLS) - Frank Lemoine (NASA/GSFC) - Josh Willis (NASA/JPL)

	Title	Presenter		
8:30 - 8:50	Review: 25 years of Sea Level Records from the Arctic Ocean Using Radar Altimetry	Rose Stine Kildegaard	Technical University of Denmark - DTU Space	DK
	Stine Kildegaard Rose[1], Ole Baltazar Andersen[1], Marcello Passaro[2], Jérôme Benveniste[3] | [1]Technical University of Denmark - DTU Space, Kgs. Lyngby, Denmark, [2]Deutsches Geodätisches Forschungsinstitut der Technischen Universität München, Munich, Germany, [3]ESA-ESRIN, Frascati, Italy			
8:50 - 9:10	Towards a Methodology for Estimating Extreme Return Levels and Its Climate Variability of Coastal Sea Level from Satellite Altimetry	Hector Lobeto	Environmental Hydraulics Institute, Universidad de Cantabria	ES
	Hector Lobeto1, Melisa Menendez[1] | [1]Environmental Hydraulics Institute, Universidad de Cantabria, Santander, Spain			
9:10 - 9:30	Understanding the Relation Between Sea Level and Bottom Pressure Variability: Recent Progress and Future Challenges	Rui Ponte	Atmospheric and Environmental Research	USA
	Rui Ponte[1], Christopher Piecuch[2] | [1]Atmospheric and Environmental Research, Inc., Lexington, United States, [2]Woods Hole Oceanographic Institution, Woods Hole, United States			
9:30 - 9:50	25 years of Wet Tropospheric Correction: Long Term Stability Assessment Using Double Difference Method	Marie-Laure Frery	CLS	FR
	Marie-laure Frery[1], Bruno Picard[1], Mathilde Siméon[1], Christophe Goldstein[2], Pierre Féménias[3], Remkoo Scharroo[4] | [1]CLS, Ramonville Saint-Agne, France, [2]Centre National d'Etudes Spatiales, Toulouse, France, [3]European Space Agency, Frascati, Italy, [4]EUMETSAT, Darmstadt, Germany			
9:50 - 10:10	Sea State Bias: 25 Years on	Christine Gommenginger	National Oceanography Centre	UK
	Christine Gommenginger[1], Meric Srokosz[1], Claire Bellingham[1], Helen Snaith[1], Nelson Pires[2], M. Joana Fernandes[2], Ngan Tran[3], Doug Vandemark[4], Thomas Moreau[3], Sylvie Labroue[3], Remko Scharroo[5] | [1]National Oceanography Centre, Southampton, United Kingdom, [2]University of Porto, Porto, Portugal, [3]Collecte Localisation Satellites, Toulouse, France, [4]University of New Hampshire, Hampshire, United States, [5]EUMETSAT, Darmstadt, Germany			
10:10 - 10:40	**Coffee Break**			

LAGOA DAS 7 CIDADES Synergy Between Altimetry, other Data and Models in Support of Operational Oceanography #3

Chairs: Joël Dorandeu (CLS), Clara Lázaro (University of Porto), Gregory Smith (Environment and Climate Change Canada)

	Title	Presenter		
8:30 - 8:50	Assimilation of High-Resolution Altimetry in a 2-km Canadian East Coast Forecasting System	Gregory Smith	Meteorological Research Division, Environment And Climate Change Canada	CA
	Gregory Smith[1], Claire Dufau[2], Mounir Benkiran[3], Yimin Liu[4], Fraser Davidson[5] | [1]Meteorological Research Division, Environment and Climate Change Canada, Dorval, Canada, [2]CLS, Toulouse, France, [3]Mercator Océan International, Toulouse, France, [4]Meteorological Service of Canada, Environment and Climate Change Canada, Dorval, Canada, [5]Fisheries and Oceans Canada, St. John's, Canada			
8:50 - 9:10	Toward New Validation Concept for High-Resolution and Coastal Altimetry: Application to the Ligurian Sea	Marco Meloni	Serco	IT
	Marco Meloni[1], Jerome Bouffard[3], Andrea Doglioli[2], Anne Petrenko[2], Guillaume Valladeau[4] | [1]Serco, Frascati, Italy, [2]MIO (Mediterranean Institute of Oceanography), Marseille, France, [3]Rhea c/o ESA-ESRIN, Frascati, Italy, [4]CLS, Toulouse, France			
9:10 - 9:30	A New Synergetic Approach for the Determination of the Sea-Surface Currents in the Mediterranean Sea	Daniele Ciani	National Research Council of Italy	IT
	Daniele Ciani[1], Marie-Hélène Rio[2], Rosalia Santoleri[1] | [1]National Research Council Of Italy, Rome, Italy, [2]Collecte Localisation Satellites, Toulouse, France			
9:30 - 9:50	Continuous Transition of Kinetic Energy Spectra and Fluxes between Mesoscale and Submesoscale	Sung Yong Kim	Korea Advanced Institute of Science And Technology	KR
	Sung Yong Kim[1] | [1]Korea Advanced Institute Of Science And Technology, Daejeon, South Korea			
9:50 - 10:10	The Malvinas Current System from 25 years of MERCATOR-Ocean Operational Reanalysis: Fronts, Recirculation Cells, Vertical Motions and Blocking Events	Camila Artana	Locean Sorbonne Universite	FR
	Camila Artana[1], Jean-Michel Lellouche[2], Young-Hyang Park[1], Gilles Garric[2], Zoé Koenig[1], Nathalie Sennéchael[1], Ramiro Ferrari[3], Alberto Piola[4], Martin Saraceno[5], Christine Provost[1] | [1]Locean Sorbonne Universite, Paris, France, [2]MERCATOR-OCEAN, Ramonville St. Agne, Frace, [3]CIMA/CONICET-UBA and UMI IFAECI-3351, Buenos Aires, Argentina, [4]Departamento de Oceanografia, Servicio de Hidrogrqfia Naval, DCAO/FCEN/UBA and UMI IFAECI-3351, CONICET, Buenos Aires, Argentina, [5]CIMA/CONICET-UBA, DCAO/FCEN/UBA and UMI IFAECI-335, Buenos Aires, Argentina			
10:10 - 10:40	**Coffee Break**			

LOGOA DO COGRO Outlook #1: Sea Level and Ocean Circulation: Continuity and Improved Resolution

Chairs: Lee-Lueng Fu (NASA/JPL) - Clément Ubelmann (CLS)

	Title	Presenter		
8:30 - 8:50	Sentinel-3A Contribution to the Continuity of Sea-Level Rise	Cristina Martin-Puig	EUMETSAT	DE
	Cristina Martin-Puig[1], Remko Scharroo[1], Carolina Nogueira-Loddo[1], Bruno Lucas[1],[2], Salvatore Dinardo[1],[2] | [1]EUMETSAT, Darmstadt, Germany, [2]HE Space, Darmstadt, Germany			
8:50 - 9:10	The Sentinel-6/Jason-CS Mission	Craig Donlon	ESA	NL
	Craig Donlon[1], Robert Cullen[1], Luisella Giulicchi[1], Pierrik Vuillemier[1], Remko Scharroo[2], [2], Eric Leuliette[3], Joshua K. Willis[4], Parag V.Vaze[4], Pascal Bonnefond[5] | [1]ESA-ESTEC, Noordwijk, The Netherlands, [2]EUMETSAT, Darmstadt, Germany, [3]NOAA, Silver Springs, United States, [4]NASA, JPL, United States, [5]Obvervatoire de Paris - SYRTE, Paris, France			
9:10 - 9:30	Observing the Ocean Surface Topography at High Resolution by the Surface Water and Ocean Topography (SWOT) Mission	Rosemary Morrow	LEGOS	USA
	Lee-lueng Fu[1], Rosemary Morrow[2] | [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, United States, [2]LEGOS, Toulouse, France			
9:30 - 9:50	Development of Hydrologic Science and Applications from the Surface Water and Ocean Topography (SWOT) Mission	Tamlin Pavelsky	Univ. of North Carolina	FR
	Tamlin Pavelsky[2], Jean-Francois Cretaux[1] | [1]CNES-LEGOS, Toulouse, France, [2]Dept of Geological Sc. Univ. of North Carolina, Chapel Hill, USA			
9:50 - 10:10	On the Spatial Scale of the Future SWOT KaRIN Measurement over the Ocean	Lee-Lueng Fu	JPL	USA
	Jinbo Wang[1], Lee-Lueng Fu[1], Hector Torres Gutierrez[1], Dimitris Menemenlis[1], Shuiming Chen[2], Bo Qiu[2] | [1]Jet Propulsion Laboratory/Caltech, Pasadena, United States, [2]University of Hawaii, Honolulu, United States			
10:10 - 10:40	**Coffee Break**			

10:40 - 12:20 | Parallel Sessions

AUDITORIUM Advances in Our Understanding of Wave Observations and Their Applications

Chairs: Saleh Abdalla (ECMWF) - Fabrice Ardhuin (LOPS) - Céline Tison (CNES)

	Title	Presenter		
10:40 - 11:00	Keynote: From Azores to Azores, 100 Years of Wave Observations for Forecasting: A Living History and Challenges Ahead	Fabrice Ardhuin	LOPS	FR
	Fabrice Ardhuin[1], Alvaro Semedo[2] | [1]LOPS, Plouzané, France, [2]IHE-Delft, Delft, The The Netherlands			
11:00 - 11:15	Incorporation of the Satellite Altimetry to the Wave Analysis, Forecast, and Verification at NWS	Stylianos Flampouris	IMSG at EMC/NCEP/ NWS/NOAA	USA
	Stylianos Flampouris[1], Jacob R. Carley[2], Deanna Spindler[1] | [1]IMSG at EMC/NCEP/NWS/NOAA, College Park, United States, [2]EMC/NCEP/NWS/NOAA, College Park, United States			
11:15 - 11:30	Detection of Ocean Whitecapping and its Variability Using Jason Radiometer and Radar Datasets	Doug Vandemark	University of New Hampshire	USA
	Doug Vandemark[1], Hui Feng[1], Bertand Chapron[2], Yves Quilfen[2] | [1]University Of New Hampshire, Durham, United States, [2]IFREMER, Plouzane, France			
11:30 - 11:45	Radar Altimeter Wind and Wave Data - Delay Doppler versus Conventional	Saleh Abdalla	ECMWF	UK
	Saleh Abdalla1 | 1ECMWF, Reading, United Kingdom			
11:45 - 12:05	REVIEW: Toward a More and More Accurate Operational Wave Forecasting System: Thanks to Altimetry	Lotfi Aouf	Meteo-France	FR
	Lotfi Aouf1, Alice Dalphinet[1], Danièle Hauser[2] | [1]Meteo-France, Toulouse, France, [2]LATMOS/CNRS, Paris, France			
12:05 - 12:20	Significant Wave Height in the Subpolar Seas of the Arctic: Monitoring Change over Two Decades with Satellite Radar Altimetry	Sinead Louise Farrell	University of Maryland	USA
	John M Kuhn[2], Kyle Duncan[1], Sinead L Farrell[1] | [1]University of Maryland / ESSIC, College Park, United States, [2]NOAA Laboratory for Satellite Altimetry, College Park, United States			

LAGOA DAS 7 CIDADES Outreach, Education and Altimetric Data Services

Chairs: Américo Ambrózio (ESA) - Jessica Hausman (NASA/JPL) - Vinca Rosmorduc (CLS) - Margaret Srinivasan (NASA/JPL)

	Title	Presenter		
10:40 - 11:00	ARGONAUTICA, an Educational Project Using JASON Data	Danielle De Staerke	CNES	FR
	Danielle De Staerke[1] | [1]Cnes, Toulouse, France			
11:00 - 11:20	25 Years of Education and Public Outreach for Ocean Radar Altimetry at NASA/Jet Propulsion Laboratory	Annie Richardson	JPL	USA
	Annie Richardson[1], Margaret Srinivasan[1] | [1]NASA-Jet Propulsion Laboratory, Pasadena, United States			
11:20 - 11:40	EUMETSAT Training in Ocean Remote Sensing	Vinca Rosmorduc	CLS	FR
	Vinca Rosmorduc[1], Christine Traeger Chatterjee[3], Hayley Evers-King[2], Ben Loveday[2] | [1]CLS, Ramonville Stagne, France, [2]Plymouth Marine Laboratory, Plymouth, United Kingdom, [3]EUMETSAT, Darmstadt, Germany			
11:40 - 12:00	The Evolution of Data Accessibility at PO.DAAC: Seasat to SWOT	Jessica Hausman	JPL	USA
	Jessica Hausman[1], Christopher Finch[1], David Moroni[1], Michael Gangl[1] | [1]JPL PO.DAAC, Pasadena, United States			
12:00 - 12:20	Twenty Five Years of User Services for Altimetry Satellite Data: Aviso Experience and Lessons Learned	Laurent Soudarin	CLS	FR
	Laurent Soudarin[1], Vinca Rosmorduc[1], Thierry Guinle[2] | [1]CLS, Ramonville Saint-agne, France, [2]CNES, Toulouse, France			

LOGOA DO CONGRO Outlook #2: Sea State, Polar Oceans and New Techniques | Chairs: Robert Cullen (ESA) - Mark Drinkwater (ESA)

	Title	Presenter		
10:40 - 11:00	CFOSAT mission, Towards the launch	Cédric Tourain	CNES	FR
	Cédric Tourain[1], Céline Tison[1], Raquel Rodriguez Suquet[1], Patrick Castillan[1], Flavien Gouillon[1] | [1]Cnes, Toulouse, France			
11:00 - 11:20	Development of a Potential Polar Ice and Snow Topography Mission	Robert Cullen	EA	NL
	Robert Cullen[1], Michael Kern[1], Gerhard Ressler[1], Ignacio Navas Traver[1], Rolv Midthassel[1], Michael Ludwig[1], Antonio Gabriele[1], Arnaud Lecuyot[1], Tania Casal[1], Tommaso Parrinello[2], Bruno Berruti[1] | [1]ESA-ESTEC, Noordwijk, The Netherlands, [2]ESA-ESRIN, Frascati, Italy			

LOGOA DO COGRO **Outlook #2: Sea State, Polar Oceans and New Techniques | Chairs: Robert Cullen (ESA) - Mark Drinkwater (ESA)**

	Title	Presenter		
11:20 - 11:40	The SKIM Mission for ESA Earth Explorer 9: a Pathfinder for Doppler Oceanography from Space	Fabrice Ardhuin	LOPS	FR
	Fabrice Ardhuin[1], The SKIM Team[1] | [1]LOPS, Plouzané, France			
11:40 - 12:00	A New Altimeter Concept for the Estimation of the Ocean Surface Directional Slopes	Jean-Claude Lalaurie	CNES	FR
	Jean-Claude Lalaurie[1], Laiba Amarouche[2], Emmanuel Fall[2] | [1]CNES, Toulouse, France, [2]CLS, Toulouse, France			
11:40 - 12:00	Radiometer for Coastal Altimetry	Rolv Midthassel	CNES	NL
	Rolv Midthassel[1], Bruno Picard[2], Massimo Labriola[3], Silvio Varchetta[4] | [1]ESA-ESTEC, Noordwijk, The Netherlands, [2]CLS, Toulouse, France, [3]Airbus Defence and Space, Madrid, Spain, [4]Thales Alenia Space , Rome, Italy			

12:30 - 14:00	**Lunch**			

14:00 - 15:40	**Plenary Closing Session Keynotes**	**Chairs: Jérôme Benveniste (ESA) - Pascal Bonnefond (Observatoire de Paris-SYRTE)**		
14:00 - 14:00	Keynotes by the winners of the 2018 Argonautica contest	Danielle De Staerke Pascal Bonnefond	CNES Observatoire de Paris-SYRTE	FR
	Danielle De Staerke[1], Pascal Bonnefond[2] | [1]CNES, Toulouse, France, [2]Observatoire de Paris-SYRTE, Paris, France			
14:00 - 14:10	Argonautica: Ocean, climate and pollution	Delegate Students	Lycée International de Valbonne	FR
	Delegate Students[1] | [1]Lycée International de Valbonne, Valbonne, France			
14:10 - 14:20	Argonautica: Naïades of the Garonne River	Delegate Students	Collège Elise Deroche	FR
	Delegate Students[1] | [1]Collège Elise Deroche, Pian sur Garonne, France			

14:00 - 15:40	Plenary Closing Session Keynotes	Chairs: Jérôme Benveniste (ESA) - Pascal Bonnefond (Observatoire de Paris-SYRTE)		
14:40 - 15:00	SARAL/AltiKa: The Emblematic Ka-Band Altimetric Mission	Jacques Verron	IGE/CNRS	FR
	Jacques A Verron[1], Pascal Bonnefond[2], Lotfi Aouf[3], Florence Birol[4], Suchandra A. Bhomwick[5], Stéphane Calmant[4], JF Crétaux[4], Gérald Dibarboure[6], AK Dubey[5], Yannice Faugère[7], Sara Fleury[4], PK Gupta[5], Raj Kumar[5], Rosemary Morrow[4], Elisabeth Rémy[8], Frédérique Rémy[4], WHF Smith[9], Jean Tounadre[10], KN Babu[5], Mathilde Cancet[11], Aditya Chaudhary[5], Frédéric Frappart[4], BJ Haines[12], Olivier Laurain[13], Annabelle Olivier[7], JC Poisson[7], Rashmi Sharma[5], Pierre Thibaut[7], C Watson[14] | [1]IGE/CNRS, Grenoble, France, [2]SYRTE, Paris, France, [3]Météo-France, Toulouse, France, [4]LEGOS, Toulouse, France, [5]SAC/ISRO, Ahmedabad, India, [6]CNES, Toulouse, France, [7]CLS, Toulouse, France, [8]Mercator-Océan, Toulouse, France, [9]NOAA, College Park, USA, [10]IFREMER, Brest, France, [11]Noveltis, Toulouse, France, [12]JPL, Pasadena, France, [13]GeoAzur, Sophia Antipolis, France, [14]University of Tasmania, Hobart, Australia			
15:00 - 15:20	The Evolution and Status of Wide-Swath Altimetry	Ernesto Rodriguez	JPL	USA
	Ernesto Rodriguez[1], Daniel Esteban-Fernandez[1], Eva Peral[1], Curtis Chen[1], Jan Willem De Blesser[1], Brent Williams[1] *[1]Jet Propulsion Laboratory, California Institute Of Technology, Pasadena, United States*			
15:20 - 15:40	Achievements and Progress in Thales Alenia Space - Radar Altimeters Product Line	Laurent Phalippou	Thales Alenia Space	FR
	Laurent Phalippou[1], Eric Caubet[1], Jacques Richard[1], Albert Cerro[1], Laurent Rey[1], Sophie Coutin-Faye[2], Alain Mallet[2], Céline Tison[2], Pierluigi Silvestrin[3], Erik De Witte[3], Robert Cullen[3] | [1]Thales Alenia Space, Toulouse, France, [2]CNES, Toulouse, France, [3]ESA, Noordwijk, The The Netherlands			
15:20 - 15:40	Benefits of New Altimetry Techniques over Non-Ocean Surfaces: A Synthesis of CLS/CNES Recent Studies	Pierre Thibaut	CLS	FR
	Pierre Thibaut[1], Thomas Moreau[1], Jérémie Aublanc[1], Fanny Piras[1], Nicolas Longepe[1], François Boy[2], Amandine Guillot[2], Sophie Le Gac[2], Nicolas Picot[2] *[1]CLS, Toulouse, France, [2]CNES, Toulouse, France*			
15:40 - 16:10	**Coffee Break**			

16:10	**Closing Session Round Tables**	
	Moderators: Barbara Ryan, ex-Secretariat Director of GEO, and Jacques Verron, IGE/U. Grenoble	
16:10 - 17:10	**Round Table 1: Future Observational Requirements**	
	Lee-Lueng Fu (JPL)	
	Benoit Meyssignac (LEGOS)	
	Joël Dorandeu (CLS)	
	David Cotton (SATоc)	
	Jean-François Crétaux (LEGOS)	
	Cécile Kittel (DTU)	
	Sinead Farrell (NOAA)	
	Rene Forsberg (DTU)	
17:10 - 18:10	**Round Table 2: Future Missions and Programmes**	
	Mark Drinkwater (ESA)	
	Juliette Lambin (CNES)	
	Eric Lindstrom (NASA)	
	Eric Leuliette (NOAA)	
	Cristian Bank (EUMETSAT)	
	Pierre-Yves LeTraon (Mercator-Ocean)	
	Mauro Facchini (EC DG-GROW)	
	Gilles Ollier (EC DG-RTD)	
18:10 - 18:20	**Closing remarks**	**Jérôme Benveniste**
18:20 - 19:00	Freshen-up	
19:00 - 23:00	**Symposium Dinner**	

1. 25 Years of Progress in Radar Altimetry: a Historical Perspective

1	A Finer Understanding of the Processes Affecting Ocean Backscatter	Graham Quartly	Plymouth Marine Laboratory	UK
	Graham Quartly[1] | 1Plymouth Marine Laboratory, Plymouth, United Kingdom			
2	Still Learning From ENVISAT 10-Year Altimetric Mission, 6 Years After Its End	Annabelle Ollivier	CLS	FR
	Annabelle Ollivier[1], Stephanie Urien[1], Nicolas Picot[2], Pierre Féménias[3], Thierry Guinle[2] | 1CLS, Ramonville, France, [2]CNES, Toulouse, France, [3]ESA-ESRIN, Frascati, Italy			
3	The Copernicus Space Infrastructure: Status & Future	Simon L. G. Jutz	ESA	IT
	Simon L. G. Jutz[1] | [1]ESA-ESRIN, Frascati, Italy			
4	ESA Fundamental Climate Data Record for ALTimetry Project (FCDR4ALT)	Pierre Féménias	ESA	IT
	"Pierre Féménias[1], Jérôme Bouffard[1], Mirko Albani[1], Gabriele Brizzi[2] | 1ESA-ESRIN, Frascati, Italy, [2]SERCO/ESA-ESRIN, Frascati, Italy			
5	Polar Altimetry	Duncan Wingham	NERC	UK
	Andrew Shepherd[1], Professor Duncan Wingham[2], Alan Muir[2], Andy Ridout[2], Lin Gibert[2], Mal McMillan[1], Racheal Tilling[1], Hannes Konrad[1], Tom Slater[1], Ines Otosaka[1], Anna Hogg[1], Noel Gourmelen[3] | [1]CPOM, Leeds, United Kingdom, [2]NERC, Swindon, United Kingdom, [3]CPOM, London, United Kingdom, [4]University of Edinburgh, Edinburgh, United Kingdom			
6	The Ocean Mean Dynamic Topography: 25 Years of Improvements	Marie-Helene Rio	CLS	FR
	Marie-helene Rio[1], Sandrine Mulet[1], Gerald Dibarbourmne[2], Nicolas Picot[2] | [1]CLS, Ramonville Saint Agne, France, [2]CNES, Toulouse, France			
7	The Younger, Thinner, Faster Arctic Sea Ice Cover: Tracking Change Over Fifteen Years	Sinead Louise Farrell	University of Maryland/ ESSIC Oregon State University/ CEOAS	USA
	Sinead Louise Farrell[1], [2], Jennifer Hutchings[3], Kyle Duncan[1], [2], Joshua McCurry[1], [2] *[1]University of Maryland/ ESSIC, College Park , United States, [2]Oregon State University/ CEOAS, Corvallis, United States, [3]NOAA Laboratory for Satellite Altimetry, College Park, United States*			
8	Twenty-Five Years of Progress in Sea Floor Mapping by Satellite Altimetry	Walter Smith	NOAA	USA
	Walter Smith, David Sandwell[2], Karen Marks[1], Ole Andersen[3] | [1]NOAA Laboratory For Satelite Altimetry, College Park, United States, [2]Scripps Institution of Oceanography, La Jolla, United States, [3]Danish Space Center, Copenhagen, Denmark			

2. Advances in our Understanding of the Open Ocean				
9	The Contribution of Barotropic Processes to the Sea Level Variability in the Southern Ocean and to the Variability of the ACC Transport Across the Kerguelen Plateau at Interannual Time Scales.	Frederic Vivier	CNRS/LOCEAN-IPSL/ Sorbonne Universités	FR
	Frederic Vivier[1], Young-Hyang Park[2], Wilbert Weijer[3] | [1]CNRS/ LOCEAN-IPSL/Sorbonne Universités, Paris, France, [2]MNHN/LOCEAN-IPSL/Sorbonne Universités, Paris, France, [3] Los Alamos National Laboratory, Los Alamos, USA			
10	A Western Tropical Atlantic Circulation Analysis Using Statistics and Satellites	Sabine Arnault	LOCEAN	FR
	Sabine Arnault[1], Sylvie Thiria[1] | [1]LOCEAN UMR CNRS IRD UPMC MNHN, Paris, France			
11	25 Year Mesoscale Eddy Trajectory Atlas on AVISO	Antoine Delepoulle	CLS	FR
	Antoine Delepoulle[1], Yannice Faugere[1], Dudley Chelton[2] | [1]CLS, Ramonville-saint-agne, France, [2]Oregon State University, Corvallis, United States			
12	Assessing Gridded Hydrographic Observations Against Satellite Data to Investigate the Southern Ocean's Mixed Layer Budget at Interannual Time Scales	Frederic Vivier	CNRS/LOCEAN-IPSL/ Sorbonne Universités	FR
	Ashray Nenaru[1],[2], Frederic Vivier[2], Nicolas Kolodziejczyk[3], Antoine Ducoin[1] | [1]LHEAA, CNRS UM6598, Ecole Centrale de Nantes, Nantes, France, [2]CNRS/LOCEAN-IPSL/ Sorbonne Universités, Paris, France, [3]UBO, UMR-6523 LPO, CNRS/Ifremer/IRD/UBO, Plouzané, France			
13	A Comparison of Global Nonstationary Semidiurnal Internal Tidal Sea Surface Height Variance between Altimeter Observations and A High Resolution Global General Circulation Model	Arin Nelson	University of Michigan	USA
	"Arin Nelson[1], Brian Arbic[1], Edward Zaron[2], Jay Shriver[3] | [1]University Of Michigan, Ann Arbor, United States, [2]Portland State University, Portland, United States, [3]Naval Research Laboratory, Stennis, United States"			
14	Spectral Signatures of the Tropical Pacific Dynamics from Model and Altimetry: A Focus on the Meso/Submesoscale Range	Lionel Gourdeau	LEGOS	FR
	Michel Tchilibou[1], Lionel Gourdeau[1], Rosemary Morrow[1], Guillaume Serazin[1], Bugshin Djath[2], Florent Lyard[1] | [1]LEGOS, Toulouse, France, [2] HZG, Geesthacht, Germany			

15	Evolution of Sea-Level Variability from Open Ocean to Coastal Zones in the South China Sea	Dongju Peng	Earth Observatory of Singapore	SG
	Dongju Peng[1], Emma Hill[1,2], Aron Meltzner[1,2], Adam Switzer[1,2] | [1]Earth Observatory Of Singapore, Nanyang Technological University, Singapore, Singapore, [2]Asian School of Environment, Nanyang Technological University, Singapore, Singapore			
16	Patterns and Variability in Sea Surface Height: Linkages to Low Frequency Variability of North Atlantic Circulation	LuAnne Thompson	University of Washington	USA
	LuAnne Thompson[1], Robert Wills[1], Kyle Armour[1], David Battisti[1], Dennis Hartmann[1] | [1]University Of Washington, Seattle, United States			
17	Altimetric Analyses of Oceanographic Pathways during El Niño Events: Connections Between the Equator and West Coasts of North and South America	Ted Strub	Oregon State University	USA
	Ted Strub[1], Corinne James[1], Craig Risien[1], Ricardo Matano[1], Vincent Combes[1] | [1]Oregon State University, Corvallis, United States			
18	Extracting Periodic Signals of the Sea Level Variations and Their Relation To Climate Indices Around Australia	Xiaoli Deng	University of Newcastle	AU
	Armin Agha Karimi[1], Xiaoli Deng[1] | [1]University Of Newcastle, Callaghan, Australia			
19	Assessment of Annual Sea Level Budget Since 2005	Hindumathi K Palanisamy	LEGOS	FR
	Hindumathi K Palanisamy[1], Anny Cazenave[1], Karina vonSchuckmann[2], William Llovel[1] | [1]LEGOS, Toulouse, France, [2]Mercator Ocean, Toulouse, France			
20	Numerical Modelling of Non-Tidal Ocean Dynamics for the Reduction of Spatio-Temporal Aliasing in Global Grids of Sea-Level Anomalies From Radar Altimetry	Henryk Dobslaw	GFZ	DE
	Henryk Dobslaw[1], Saskia Esselborn[1] | [1]Deutsches GeoForschungsZentrum (GFZ), Potsdam, Germany			
21	Complementing Satellite Altimeter Measurements with AIS Data to more Precisely Monitor the Aghulas Current	Clément Le Goff	E-odyn	FR
	Clément Le Goff[1], Bertrand Chapron[2], Tournadre Jean[2], Guichoux Yann[1] | [1]E-odyn, Plouzane, France, [2]Ifremer LOPS, Plouzane, France			

22	Satellite Altimeter Combined Measurements and Local Persistent Small-Scale Ocean-Atmosphere Signatures	Yves Quilfen	Laboratoire d'Océanographie Physique et Spatiale	RU
	Yves Quilfen[1], Bertrand Chapron[1], Fabrice Ardhuin[1], Maria Yurovskaya[2] | [1]Laboratoire d'Océanographie Physique et Spatiale, Plouzané, France, [2]Marine Hydrophysical Institute RAS, Sebastopol, Russia			
23	Global Wavenumber Spectra from SARAL/Altika and Sentinel-3 Observations	Oscar Vergara	LEGOS IRD/CNES/CNRS/ University of Toulouse	FR
	Oscar Vergara[1], Rosemary Morrow[1], Isabelle Pujol[2], Gerlad Dibarboure[3] | [1]LEGOS IRD/CNES/CNRS/University of Toulouse, Toulouse, France, 2CLS Space Oceanography, Toulouse, France, [3]CNES, Toulouse, France			
24	Ocean Meso Scale in the Copernicus Marine Environment Monitoring Service Global Ocean Eddy-Resolving Physical Analysis, Forecasting and Reanalysis	Yann Drillet	Mercator Ocean	FR
	Yann Drillet[1], Jean Michel Lellouche[1], Romain Bourdalle Badie[1] | [1]Mercator Ocean, Ramonville St Agne, France			
25	ACC Circulation and its Variability in the Udintsev Fracture Zone From Altimetry and in Situ Observations	Young-Hyang Park	LOCEAN, Sorbonne Université	FR
	Young-Hyang Park[1], Christine Provostn[1], Isabelle Durand1, Jae-Hak Lee[2], Sang-Hoon Lee[3], Isabelle Pujol[4], Jean-Michel Lellouche[5], Gilles Garric[5] | [1]LOCEAN, Sorbonne Université, Paris, France, [2]KIOST, Pusan, Korea, [3]KOPRI, Incheon, Korea, [4]CLS, Toulouse, France, 5MERCATOR-OCEAN, Ramonville St. Agne, France			
26	High Resolution Tidal Modelling at Regional Scales	Mathilde Cancet	NOVELTIS	FR
	Mathilde Cancet[1], Florent Lyard[2], Florence Toublanc[1] | [1]NOVELTIS, Labège, France, [2]LEGOS, Toulouse, France			
27	Surface Film Thickness From Ku/C Band Backscatter Relation	Jean Tournadre	IFREMER	FR
	Jean Tournadre[1], Doug Vandemark[2], Feng Hui2, Bertrand Chapron[1] | [1]IFREMER, Plouzané, France, [2]University New-Hampshire, Durham, USA			
28	Sea Level and Ocean Heat Content Variations of the Antarctic Continental Shelf	Ichiro Fukumor	JPL	USA
	Ichiro Fukumori[1], Ou Wang[1], Ian Fenty[1] | [1]JPL, Pasadena, United States			
29	Interannual Variability of Mesoscale Eddy Kinetic Energy in the Indian and Pacific Oceans	Andrew Delman	JPL	USA
	Andrew Delman[1], Tong Lee[1], Bo Qiu[2] | [1]JPL, Pasadena, United States, [2]University of Hawaii at Mãnoa, Honolulu, United States			
30	Diagnosing the Drivers of Regional Decadal Sea Level Change With ECCO	Philip Thompson	University of Hawaii	USA
	Philip Thompson[1], Chris Piecuch[2], Rui Ponte[3], Mark Merrifield[4] | [1]University Of Hawaii, Honolulu, United States, [2]Woods Hole Oceanographic Institution, Woods Hole, United States, [3]Atmospheric and Environmental Research, Inc., Lexington, United States, [4]Scripps Institution of Oceanography, UC San Diego, San Diego, United States			

31	How Does Resolution and Data Assimilation Affect the Predictability of Internal Tides in a Global Ocean Circulation Model?	Maarten Buijsman	University Of Southern Mississippi	USA

Maarten Buijsman[1], Jay Shriver[2], Gordon Stephenson[1], Chan-Hoo Jeon[1], Brian Arbic[3], James Richman[4] | [1]University Of Southern Mississippi, Stennis Space Center, United States, [2]Naval Research Laboratory, Stennis Space Center, United States, [3]University of Michigan, Ann Arbor, United States, [4]Florida State University, Tallahassee, United States

32	25 years of Monitoring the Antarctic Circumpolar Current at Drake Passage	Zoé Koenig	LOCEAN/Sorbonne Universite/CNRS/UPMC	FR

Zoé Koenig1, Camila Artana1, Ramiro Ferrari[2], Nathalie Sennéchael1, Young-Hyang Park[1], Gilles Garric[3], Christine Provost[1] | [1]LOCEAN Sorbonne Universite/CNRS/UPMC, Paris, France, [2]CIMA-CONICET/UBA, Buenos Aires, Argentina, [3]Mercator Ocean, Ramonville Saint Agne, France

33	25 Years of Malvinas Current Volume Transport at its Northernmost Extension: Variability and Drivers	Camila Artana	LOCEAN Sorbonne Universite	FR

Camila Artana[1], Ramiro Ferrari[2], Zoé Koenig[1], Nathalie Sennéchael[1], Martin Saraceno[3], Alberto Piola[4], Christine Provost[1] | [1]LOCEAN Sorbonne Universite, Paris, France, [2]CIMA/CONICET-UBA and UMI-IFAECI-3351, Buenos Aires, Argentina, [3]CIMA/CONICET-UBA, DCAO/FCEN/UBA and UMI IFAECI-3351, Argentina, [4]Departamento de Oceanografia, Servicio de Hidrografía Naval, DCAO/FCEN/UBA and UMI-IFAECI-3351, CONICET, Argentina

34	A Regional Analysis of the West Tropical Atlantic Ocean Variability	Fabrice Hernandez	IRD/LEGOS/Mercator Océan	FR

Fabrice Hernandez[1], Minto Dimoune[2,3], Julia Araujo[2], Moacyr Araujo[2,4] | [1]IRD/LEGOS/Mercator Océan, Ramonville St Agne, France, [2]Laboratório de Oceanografia Física Estuarina e Costeira (LOFEC), Department of Oceanography – DOCEAN, Federal University of Pernambuco , Recife, Brazil, [3]International Chair in Mathematical Physics and Applications (ICMPA-Unesco Chair), UAC, Cotonou, Benin, [4]Brazilian Research Network on Global Climate Change – Rede CLIMA, São José dos Campos, Brazil

35	Near-Real Time and a 25-Year Reanalysis of Global Ocean Currents at the Surface and 15m Depth From the Synergetic Use of Altimetry, GOCE, Wind and In-Situ Data	Marie-Helene Rio	CLS	FR

Marie-Helene Rio[1], Helene Etienne[1], Claire Dufau[1], Craig Donlon[2] | [1]CLS, Ramonville Saint Agne, France, [2]ESA-ESTEC, Nordwijk, The Netherlands

36	On the Relative Information Content of Surface Data versus Interior Data in Constraining the Large-Scale Ocean Circulation and Its Variability	Remi Tailleux	University of Reading	UK

Remi Tailleux[1], Keith Haines[1], Shaun Lee[1] | [1]University Of Reading, Reading, United Kingdom

37	Sea Level in the Mediterranean and Black Seas: the Regional Imprints of Large-Scale Atmospheric and Oceanic Dynamics	Denis Volkov	University of Miami	USA

Denis Volkov[1,2], Felix Landerer[3] | [1]University Of Miami-CIMAS, Miami, United States, [2]NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, United States, [3]JPL, Pasadena, United States

38	High-Wavenumber Variability in the Eastern Tropical Pacific from ADCP and Altimetry	Saulo Soares	University of California San Diego	USA
	Saulo Soares[1], Sarah Gille[1], Teresa Chereskin[1], Cesar Rocha[1] | [1]University Of California San Diego, La Jolla, United States			
39	Quantifying Atlantic Water Transport to the Nordic Seas by Combined Use of Gravimetry and Altimetry	Roshin R. Raj	Nansen Center	NO
	Roshin R. Raj[1], Jan Even Ø. Nilsen[1], Johnny A. Johannessen[1], Tore Furevik[2], Ole B. Andersen[3], Laurent Bertino[1] | [1]Nansen Center, Bergen, Norway, [2]Bjerknes Center for Climate Research, Bergen, Norway, [3]Danish Technical University, Copenhagen, Denmark			
40	Advances in Studies of Upper Ocean Mesoscale Processes and Dynamics from Satellite Sensor Synergy: The GlobCurrent Findings	Johnny A. Johannessen	Nansen Center	NO
	Johnny A. Johannessen[1], Bertrand Chapron[2], Fabrice Collard[3], Marie-Helene Rio[4], Lucille Gaultier[3], Graham Quartly[5], Craig Donlon[6] | [1]Nansen Center, Bergen, Norway, [2]Ifremer, Brest, France, 3OceanDataLab, Brest, France, [4]CLS, Toulouse, France, [5]PML, Plymouth, UK, [6]ESA, Noorwijk, The Netherlands			
41	How Can SWOT Better Reconstruct Horizontal and Vertical Velocities?	Babette Christelle Tchonang	Mercator Ocean | CNES	FR
	Babette Christelle Tchonang[1,2], Pierre-Yves Le Traon[1,3], Mounir Benkiran[1], Giovanni Gruggiero[1] | [1]Mercator Ocean , Ramonville Saint Agne, France, [2]CNES, Toulouse, France, [3]IFREMER, Brest, France			
42	From Past and Present Nadir Altimetry Constellations to the SWOT Era : What is the True Effective Resolution of Altimetry?	Clement Ubelmann	CLS	FR
	Clement Ubelmann[1], Maxime Ballarotta[1], Yannice Faugere[1], Gerald Dibarboure[2] | [1]CLS, Ramonville, France, [2]CNES, Toulouse, France			
43	Assessment of Mesoscale Resolution Capability of Sentinel 3 and SARAL Altimeters with Respect to Kilometric-Scale Ocean Simulations.	Laurent Brodeau	Ocean Next	FR
	Laurent Brodeau[1], Julien Le Sommer[2], Jacques Verron[1,2], Adekunle Ajayi[2], Clément Ubelmann[3], Gerald Dibarboure[4] | [1]Ocean Next, Grenoble, France, [2]IGE/MEOM, Grenoble, France, [3]CLS Space Oceanography, Toulouse, France, [4]CNES, Toulouse, France			
44	AMOC from Space: The Importance of Synergy of Satellite and In-Situ Measurements	Shenfu Dong	AOML	USA
	Shenfu Dong[1], Gustavo Goni[1], Hosmay Lopez[1,2], Molly Baringer[1] | [1]AOML, National Oceanic and Atmospheric Administration, Miami, United States, [2]CIMAS, University of Miami, Miami, United States			
45	Mesoscale Eddies in Australian-Antarctic Basin Based on Altimetry Data	Nikita Sandalyuk	Saint Petersburg State University	RU
	Nikita Sandalyuk[1], Tatyana Belonenko[1] | [1]Saint Petersburg State University, Saint Petersburg, Russian Federation			

3. Advances in Our Understanding of Coastal Processes

46	An Improved Satellite Altimetry Data Processing Dedicated to Coastal Areas: Validation over Algerian Coast	Ali Ram	Centre of Space Techniques	DZ
	Ali Rami[1], Touati Benkouider[1] | [1]Centre Of Space Techniques, Oran, Algeria			
47	ALES Retracking Results for Sentinel-3A PLRM and SARAL/Altika Missions	Nadim Dayoub	National Oceanography Centre	UK
	Nadim Dayoub[1], Chris Banks[1], Francisco Mir Calafat[1], Christine Gommenginger[1], Helen Snaith[1], Paolo Cipollini[2], Andrew Shaw[3] | [1]National Oceanography Centre, Southampton/ Liverpool, United Kingdom, [2]Telespazio VEGA UK for ESA/ECSAT , Oxfordshire, United Kingdom, [3]SKYMAT Ltd, Southampton, United Kingdom			
48	Satellite Altimetry and Coastal Predictions of Atmosphere, Ocean and Wind Waves	Emil Stanev	HZG	DE
	Emil Stanev[1] | [1]HZG, Geesthacht , Germany			
49	Greenlandic Coastal Sea Ice Freeboard and Thickness From CryoSat-2 SARIn Data	Alessandro Di Bella	DTU Space | JPL	DE/USA
	Alessandro Di Bella[1],[2], Ron Kwok[2], Thomas Armitage[2], Henriette Skourup[1], Rene Forsberg[1] | [1]DTU Space, National Space Institute, Kgs. Lyngby, Denmark, 2JPL, Pasadena, United States			
50	Assessment of Ionosphere TEC Determination From Dual-Frequency Altimetry Missions With Reference to Local and Global GNSS-TEC Models in Coastal Regions	Wojciech Jarmołowski	University of Warmia And Mazury in Olsztyn	PL
	Wojciech Jarmołowski[1], Paweł Wielgosz[1], Xiaodong Ren[2], Anna Krypiak-Gregorczyk[1] | [1]University Of Warmia And Mazury In Olsztyn, Olsztyn, Poland, [2]Wuhan University, Wuhan, China			
51	The Low-Frequency Variability of the Agulhas Bank Circulation	Ricardo Matano	CEOAS	USA
	Ricardo Matano[1], Vincent Combes[1], Ted Strub[1], Corinne James[1] | [1]CEOAS, Oregon State University, Corvallis, United States			
52	Cross-Calibration of Retracked Jason-2 and Sentinel-3A SAR Sea Surface Heights Around Australia	Fukai Peng	University of Newcastle	AU
	Fukai Peng[1], Xiaoli Deng[1] | [1]The University of Newcastle, Australia, Newcastle, Australia			

53	Developments in SAR Altimetry Over Coastal and Open Ocean: A Retrospective of Developments in SAR Altimetry Processing and the Improvements Achieved Through the SAMOSA, CP40 and SCOOP Projects	David Cotton	Satellite Oceanographic Consultants	UK

David Cotton[1], Thomas Moreau[2], Matthias Raynal[2], Eduard Makhoul[3], Mathilde Cancet[4], Luciana Fenoglio-Marc[5], Salvatore Dinardo[6], Marc Naeije[7], M Joana Fernandes[8], Clara Lazaro[8], Andrew Shaw[9], Paolo Cipollini[10], Christine Gommenginger[11], Pablo Nilo Garcia[18], Francisco Martin[12], Alejandro Egido[13], Francois Boy[14], Nicolas Picot[14], Ole Andersen[15], Lars Stenseng[15], Cristina Martin Puig[12], Philippa Berry[16], Keith Raney[17], Chris Ray[18], Marco Restano[19], Américo Ambrózio[20], Jérôme Benveniste[21] | [1]Satellite Oceanographic Consultants, Stockport, United Kingdom, 2CLS, Ramonville Saint-Agne, France, [3]IsardSAT, Guildford, UK, [4]Noveltis, Labège, France, [5]University of Bonn, Bonn, Germany, [6]TU Darmstadt, HeSpace / EUMETSAT, Darmstadt, Germany, [7]Delft University of Technology, Delft, The The Netherlands, [8]University of Porto, Porto, Portugal, [9]SKYMAT, Southampton, UK, [10]Telespazio VEGA / ECSAT, Harwell, UK, [11]National Oceanography Centre, Southampton, UK, [12]CGI / EUMETSAT, Darmstadt, Germany, [13]NOAA, Silver Springs, USA, [14]CNES, Toulouse, France, [15]DTU Space, Copenhagen, Denmark, [16]Roch Remote Sensing, Leicester, UK, [17]2kR-LLC, Annapolis, USA, [18]IsardSAT, Barcelona, Spain, [19]SERCO/ESA-ESRIN, Frascati, Italy, [20]DEIMOS/ESA-ESRIN, Frascati, Italy, [21]ESA-ESRIN, Frascati, Italy

54	Estimated of Background Concentration of Dissolved Oil-Hydrocarbons in the Baltic Sea from Illegal Discharges of Oil-Containing Waste from Ships	Sergey Lebedev	GC RAS | Maykop State Technological University	RU

Sergey Lebedev[1],[2] | [1]GC RAS, Moscow, Russian Federation, [2]Maykop State Technological University, Maykop, Russian Federation

55	Interannual Variability of the Black Sea level and Surface Temperature along the Coast of the Krasnodar Krai and the Republic of Abkhazia Based on Satellite Altimetry and Radiometry	Sergey Lebedev	GC RAS | Maykop State Technological University	RU

Sergey Lebedev[1],[2], Andrey Kostianoy[3], Asida Akhsalba[4], Pavel Kravchenko[5] | [1]GC RAS, Moscow, Russian Federation, [2]Maykop State Technological University, Maykop, Russian Federation, [3]P.P.Shirshov Institute of Oceanology of the Russian Academy of Sciences, Moscow, Russian Federation, [4]Abkhazian State University, Sukhum, Abkhazia, [5]Tver State University, Tver, Russian Federation

56	Processing Method of Satellite Altimetry Data for White, Barents and Kara Seas	Sergey Lebedev	GC RAS | Maykop State Technological University	RU

Sergey Lebedev[1],[2] | [1]GC RAS, Moscow, Russian Federation, [2]Maykop State Technological University, Maykop, Russian Federation

57	Validation of Coastal Sea Level Rates from Dedicated Coastal Altimetry Products	Andrew Shaw	SKYMAT Ltd	UK

Andrew Shaw[1], Francisco Mir Calafat[2], Nadim Dayoub[2], Paolo Cipollini[3], Jérôme Benveniste[4] | [1]SKYMAT Ltd, Southampton, United Kingdom, [2]National Oceanography Centre, Southampton, United Kingdom, [3]Telespazio VEGA for ESA-ECSA, Luton, United Kingdom, [4]ESA-ESRIN, Frascati, Italy

58	High Resolution Coastal Wave Model for the West-Indies under Major Hurricanes of 2017	Alice Dalphinet	Meteo-France	FR
	Alice Dalphinet[1], Lotfi Aouf[1], Robert Osinski[1], Héloïse Michaud[2] | [1]Meteo-France, France, [2]SHOM, France			
59	Evaluation of the Impact of High Frequency Radar Data Assimialtion on SSH Forecast	Jaime Hernandez Lasheras	SOCIB	ES
	Jaime Hernandez Lasheras[1], Baptiste Mourre[1], Emma Reyes[1], Jano Orfila[2], Joaquin Tintoré[1,2] | [1]SOCIB, Palma De Mallorca, Spain, [2]IMEDEA, Esporles, Spain			
60	S3 SAR Mode for Coastal Altimetry. Dedicated Algorithms for Improving Sea Surface Height Series	Pablo Garcia	Isardsat SL	ES
	Pablo Garcia[1], Eduard Makhoul1, Mònica Roca[1] | [1]Isardsat SL, Barcelona, Spain			
61	GNSS-R Altimetry for Support of Coastal Altimetry	Kaoru Ichikawa	Kyushu University	JP
	Kaoru Ichikawa[1], Takuji Ebinuma[2], GROWTH team | 1RIAM, Kyushu University, Kasuga, Japan, [2]College of Engineering, Chubu University, Kasugai, Japan			
62	Assimilation of Altimeter Observations into the Navy Coastal Ocean Model	Hans Ngodock	The Us Naval Research Laboratory	USA
	Hans Ngodock[1], Matthew Carrier[1], Scott Smith[1] | [1]The Us Naval Research Laboratory, Stennis Space Center, United States			
63	Contribution of Satellite Radar Altimetry for Land Deformation Studies	Ting-Yi Yang	Ohio State University	USA
	Ting-Yi Yang[1], C.K. Shum[1,2], Yuanyuan Jia[1], Alexander Braun[3], Yuchan Yi1, Cheinway Hwang[4], Chungyen Kuo[5], Kuo-Hsin Tseng[6], Yuande Yang7, Chunxi Guo[8], Jianliang Nie[8] | [1]The Ohio State University, Columbus, United States, [2]Chinese Academy of Sciences, China, [3]Queen's University, Canada, [4]National Chiao Tung University, Taiwan, [5]National Cheng Kung University, Taiwan, [6]National Central University, Taiwan, [7]Wuhan University, China, [8]Centre for Geodetic Data Processing, China			
64	Validating Altimeter Estimates of Sea Level Along the Southern Coast of Australia	Madeleine Cahill	CSIRO	AU
	Madeleine Cahill[1], Claire Dufau[2], Gerald Dibarboure[3], Benoit Legresy[1] | [1]CSIRO, Battery Point, Australia, [2]CLS, Toulouse, France, [3]CNES, Toulouse, France			
65	Last Developments and Perspectives of the X-TRACK Regional Altimeter Products	Fabien Léger	LEGOS / CTOH	FR
	Fabien Léger[1], Florence Birol[1], Fernando Niño[1], Sara Fleury[1], Marcello Passaro[2] | [1]LEGOS/CTOH, Toulouse, France, [2]DGFI-TUM, Munich, Germany			
66	Absolute Water Levels at the Estuary of the Karnaphuli River (Bay of Bengal, Bangladesh): Comparison Between Sea / River Surface Heights Gained by GNSS Survey and Satellite Altimetry in Coastal Environment	Marufa Ishaque	BSMR Maritime University	BD
	Marufa Ishaque[1], Daniel Moreira[2], Stephane Calmant[2], Fabien Durand[2], Laurent Testut[2,3], Yann Krien[4], Valerie Ballu[3], Fabrice Papa[2] | [1]BSMR Maritime University, Dhaka, Bangladesh, [2]LEGOS, Toulouse, France, [3]LIENSs, La Rochelle, France, [4]LARGE, University des Antilles, Guadeloupe, France			

4. Advances in Our Understanding of Wave Observations and Their Applications				
67	Wind and Wave Climate from 32-Years of Satellite Altimetry	Doug Vandemark	UNH	USA
	Justin Stopa[1,2], Doug Vandemark[2], Fabrice Ardhuin[1], Bertrand Chapron[1] | [1]LOPS, Plouzane, France, [2]UNH, Durham, United States			
68	Wave Steepness from Satellite Altimetry for Wave Dynamics and Climate Studies	Sergei Badulin	Shirshov Institute of Oceanology Novosibirsk State University	RU
	Sergei Badulin[1,2], Vika Grigorieva[1] | [1]Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russian Federation, [2]Laboratory of Nonlinear Wave Processes, Novosibirsk State University, Novosibirsk , Russian Federation			
69	CFOSAT : A New Satellite for Ocean/Atmosphere Interaction Research and Operational Oceanography	Danièle Hauser	LATMOS	FR
	Danièle Hauser[1], Céline Tison[2], Alexis Mouche[3], Lotfi Aouf[4], Bertrand Chapron[3], Cedric Tourain[2] | [1]LATMOS (CNRS -UVSQ- Sorbonne-Université), Guyancourt, France, [2]CNES, Toulouse, France, [3]Ifremer, Brest, France, [4]Meteo-France, , France			
70	Radar Altimeter Signatures of Internal Solitary Waves in the Ocean	José Da Silva	University Of Porto	PT
	José Da Silva1, Adriana Santos-Ferreira1, Meric Srokosz[2], Jean Tournadre[3], Bertrand Chapron[3] | [1]University Of Porto, Porto, Portugal, [2]National Oceanography Centre, Southampton, Southampton, U.K., [3]IFREMER, , France			
71	Advances in Using Satellite Altimetry to Enhance Monitoring and Prediction of Storm Surges	Guoqi Han	Fisheries and Oceans Canada	CA
	Guoqi Han[1] | [1]Fisheries And Oceans Canada, St. John's, Canada			
72	The Sea State Climate Change Initiative Project	The Sea State CCI Team	LOPS	FR
	The Sea State CCI Team[1] | [1]LOPS, Plouzané, France			
73	Status of the Surface Wave Investigation and Monitoring (SWIM) Instrument	Benjamin Carayon	Thales Alenia Space	FR
	Benjamin Carayon[1], Laurent Rey[1], Thierry Amiot[2], Céline Tison[2], Patrick Castillan[2] | [1]Thales Alenia Space, Toulouse, France, [2]CNES, Toulouse, France			

74	Ocean Wave Data Assimilation at ECMWF: A Review	Saleh Abdalla	ECMWF	UK
	Saleh Abdalla[1], Jean-Raymond Bidlot[1] | 1ECMWF, Reading, United Kingdom			
75	Impact of Vertical Sea Wave Orbital Velocities on SAR Altimetry	Christopher Buchhaupt	TU Darmstadt	DE
	Christopher Buchhaupt[1], Luciana Fenoglio[2], Salvatore Dinardo[5], Remko Scharroo[3], Jerome Benveniste[4], Matthias Becker[1] | [1]TU Darmstadt, Darmstadt, Germany, [2]University of Bonn, Bonn, Germany, [3]EUMETSAT, Darmstadt, Germany, [4]ESA-ESRIN, Frascati, Italy, [5]He Space-EUMETSAT, Darmstadt, Germany			
76	New Wave Near-Real-Time Observational Products Derived From Altimetry and SAR	Elodie Charles	CLS	FR
	Elodie Charles[1], Romain Husson[2], Nicolas Taburet[1], Alexis Mouche[3] | [1]CLS, Ramonville Saint-Agne, France, [2]CLS, Brest, France, [3]IFREMER, Brest, France			
77	Synergy Between Satellite Observations and Model Simulations During Extreme Events	Joanna Staneva	HZG	DE
	Joanna Staneva[1], Anne Wiese[1], Arno Behres[1], Johannes Schulz-Stellenfleth[1], Luciana Fenoglio-Marc[2] | [1]Helmholz Zentrum Geesthacht, Geesthacht, Germany, [2]University of Bonn, Bonn, Germany			
78	From Gravity Waves to Mesoscales: Broadband Measurements of Ocean Surface Topography Using Airborne Lidar Technology	Kendall Melville	Scripps Institution of Oceanography	USA
	Kendall Melville[1], Luc Lenain[1], Nick Statom[1] | [1]Scripps Institution of Oceanography, La Jolla, United States			
79	Mixing, Restratification and Heat Uptake in Tropical Cyclones Wake : Processes and Contribution of Multiplatform Satellite	Clément Combot	LOPS-SIAM IFREMER	FR
	Clément Combot[1], Yves Quilfen[1], Bertrand Chapron[1], Alexis Mouche[1] | [1]LOPS-SIAM IFREMER, Brest, France			
80	Characterization of the Wind Drop-Off in Coastal Eastern Boundary Upwelling System Using Surface Winds from Radar Altimetry	Frédéric Frappart	GET LEGOSt	FR
	Frédéric Frappart[1,2], Orlando Astudillo[2,3], Abderrahim Bentamy[4], Boris Dewitte[2,3,5,6], Marc Mallet[7], José Ruttlant[3,5], Marcel Ramos[3,6], Luis Bravo[6], Katerina Goubanova[3,6,8], Serena Illig[2,9] | [1]GET, Toulouse, France, [2]LEGOS, Toulouse, France, [3]CEAZA, La Serena, Chile, [4]IFREMER, Brest, France, [5]Universidad de Chile, Santiago, Chile, [6]Universidad Católica del Norte, Coquimbo, Chile, [7]CNRM, Toulouse, France, [8]CERFACS, Toulouse, France, [9]University of Cape Town, Cape Town, South Africa			
81	Assessment of Severe Waves with Satellite Altimetry Data and Doppler Radar Observations in the North Sea	Sonia Ponce De Leon Alvarez	CENTEC-Centre for Marine Technology and Ocean Engineering	PR
	Sonia Ponce De Leon Alvarez[1], Joao Bettencourt[1], Frederic Dias[2] | [1]CENTEC-Centre for Marine Technology and Ocean Engineering, Lisbon, Portugal, [2]University College Dublin, Dublin, Ireland			

5. Altimetric Contributions to Gravity Field, Marine Geodesy, Bathymetry Modeling

82	Mean Dynamic Topography Determination Using Saral/Altika Altimetry Data and GOCE Gravity Model	Ali Rami	Centre of Space Techniques	DZ
	Ali Rami[1], Touati Benkouider[1], Faouzi Berrichi[1] | [1]Centre of Space Techniques, Oran, Algeria			
83	Mean Sea Surface: A Constant Evolution Over the Last 25 Years	Philippe Schaeffer	CLS	FR
	Philippe Schaeffer[1], Isabelle Pujol[1], Yannice Faugère[1], Nicolas Picot[2], David Sandwell[3], Gerald Dibarboure[2] | [1]CLS, Ramonville, France, [2]CNES, Toulouse, France, [3]Scripps Inst. of Oceanography, La Jolla, CA, USA			
84	Mean Sea Level and Mean Dynamic Topography Determination From Cryosat-2 Data Around Australia	Xiaoli Deng	University of Newcastle	AU
	Armin Agha Karimi[1], Ole Baltazar Andersen[2], Xiaoli Deng[1] | [1]University Of Newcastle, Callaghan, Australia, [2]DTU Space, National Space Institute, Lyngby, Denmark			
85	Indirect Mapping of Sub-Water Interfaces Derived from Satellite Altimetry: From Seafloor to River Channels	Adrien Paris	CLS LEGOS	FR
	Adrien Paris[1,2], Pierre-André Garambois[3], Stéphane Calmant[2], Amanda Montazem[2], Jérôme Monnier[4] | [1]CLS, Ramonville, France, Ramonville Saint Agne, France, [2]LEGOS, Université de Toulouse, IRD, CNES, CNRS, UPS, Toulouse, France, [3]ICUBE-UMR 7357, Fluid Mechanics Team, INSA, Strasbourg, France, [4]IMT UMR5219, INSA, Toulouse, France			
86	A Coastal Mean Sea Surface with Associated Errors Along the Norwegian Coast Based on New-Generation Altimetry	Vegard Ophaug	NMBU	NO
	Vegard Ophaug[1], Kristian Breili[1,2], Ole Baltazar Andersen[3] | [1]Faculty of Science and Technology (RealTek), Norwegian University of Life Sciences (NMBU), As, Norway, [2]Geodetic Institute, Norwegian Mapping Authority, Hønefoss, Norway, [3]DTU Space, Technical University of Denmark, Lyngby, Denmark			
87	Improved Arctic Ocean Bathymetry and Regional Tide Atlas – a CP40 Initiative	Ole Baltazar Andersen	DTU Space	DK
	Ole Baltazar Andersen[1], Mathilde Cancet[2], David Cotton[3], Jerome Benveniste[4] | [1]DTU Space, Kongens Lyngby, Denmark, [2]Noveltis, Toulouse, France, [3]SatOc, United Kingdom, [4]ESA-ESRIN, Frascati, Italy			
88	A New DTU18 MSS Mean Sea Surface – Improvement From SAR Altimetry	Ole Baltazar Andersen	DTU Space	DK
	Ole Baltazar Andersen[1], Per Knudsen[1], Lars Stenseng[1] | [1]DTU Space, Kongens Lyngby, Denmark			
89	High Resolution Gravity Field Modelling Using SAR Altimetry in the Northeast Atlantic Ocean	Marie-Francoise Lalancette	SHOM	FR
	Ole Baltazar Andersen[1], Marie-Francoise Lalancette[2], Corinne Salaun[2], Mathilde Cancet[3] | [1]DTU Space, Kongens Lyngby, Denmark, [2]SHOM, France, [3]Noveltis, France			

90	Global and Regional Evaluation of the First Two Years of Sentinel-3A and Very First Sentinel-3B and the Impact of Mean Sea Surfaces and Ocean Tide Corrections	Ole Baltazar Andersen	DTU Space	DK
	Ole Baltazar Andersen[1], Heidi Ranndal[1] | 1DTU Space, Kongens Lyngby, Denmark			
91	The Contribution of DTU17 Marine Gravity for the Arctic Bathymetry Prediction	Adil Abulaitijiang	DTU Space	DK
	Adil Abulaitijiang[1], Ole Andersen[1], David Cotton[2], Mathilde Cancet[3], Jerome Benveniste[4] | [1]DTU Space, Kongens Lyngby, Denmark, [2]SatOc, , United Kingdom, [3]Noveltis, Toulouse, France, [4]ESA-ESRIN, Frascati, Italy			
6. Precise Orbit Determination				
92	REAPER Re-Scoped: Updated Orbit Solutions for the Full ERS-1 and ERS-2 Mission Periods	Pieter Visser	Delft University of Technology	NL
	Pieter Visser[1], Michiel Otten[2] | [1]Delft University Of Technology, Delft, The Netherlands, [2]PosiTim UG, Seeheim-Jugenheim, Germany			
93	Reprocessing of TOPEX/Poseidon Precise Orbits in the CNES GDR-F Standards	Clément Masson	CS SI	FR
	Clément Masson[1], Alexandre Couhert[2], John Moyard[2], Flavien Mercier[2], Eva Jalabert[2] | [1]CS SI, Toulouse, France, [2]CNES, Toulouse, France			
94	Improved GNSS Phase Maps in Flight Modelling and Identification, Application on Jason-2 and Jason-3	Hanane Ait Lakbir	CS SI	FR
	Hanane Ait Lakbir[1], Flavien Mercier[2], Alexandre Couhert[2] | [1]CS SI, Toulouse, France, [2]CNES, Toulouse, France			
95	First Orbit Determination Results for Sentinel-3B	Heike Pete	Positim UG	DE
	Heike Peter[1], Jaime Fernández[2], Pierre Féménias[3] | [1]Positim UG, Seeheim-Jugenheim, Germany, [2]GMV AD, Tres Cantos, Spain, [3]ESA-ESRIN, Frascati, Italy			
96	Latest Results From the Geomed2 Project: Geoid and the DOT in the Mediterranean Area	Riccardo Barzaghi	Politecnico di Milano	IT
	Riccardo Barzaghi[1], Geomed[2] Team | [1]Politecnico di Milano, Milan, Italy			
97	The Geomed2 Combined Geoid Model	Sean Bruinsma	CNES	FR
	Sean Bruinsma[1], George Vergos[2], Franck Reinquin[1], Ilias Tziavos[2], Riccardo Barzaghi[3], Daniela Carrion[3], Sylvain Bonvalot[4], Lucia Seoane[4], Marie-Françoise Lequentrec-Lalancette[5], Corinne Salaun[5], Per Knudsen[6], Ole Andersen[6], Marie-Helene Rio[7] | [1]CNES, Toulouse, France, [2]Aristotle University of Thessaloniki, Thessaloniki, Greece, [3]Politecnico di Milano, Milan, Italy, [4]GET UMR 5563, Toulouse, France, [5]SHOM, Brest, France, [6]DTU Space, Kopenhagen, Denmark, [7]CLS, Ramonville Saint Agne, France			

98	Orbit Validation of Sentinel-3 Mission	Jaime Fernández	GMV AD	DE
	Jaime Fernández[2], Heike Peter[1], Pierre Féménias[3], Copernicus POD QWG team | [1]Positim UG, Swisttal, Germany, [2]GMV AD, Tres Cantos, Spain, [3]ESA-ESRIN, Frascati, Italy			
99	Generating Precise and Homogeneous Orbits for ESA's Altimetry Missions: ERS-1, ERS-2, Envisat, Cryosat-2, and Sentinel-3A	Michiel Otten	ESA	DE
	Michiel Otten[1], Claudia Flohrer[1], Tim Springer[1], Werner Enderle[1] | [1]ESA-ESOC, Darmstadt, Germany			
100	Jason-3 and Sentinel-3A GPS Processing Using Zero-Difference Integer Ambiguity Fixing	Flavien Mercier	CNES	FR
	Flavien Mercier[1], Hanane Ait-Lakbir, Clément Masson, Alexandre Couhert | [1]CNES, Toulouse Cedex 9, France			
101	Precise Orbit Determination of the Sentinel Sattelites With Gipsy-Oasis	Wim Simons	Delft University of Technology	NL
	Wim Simons[1], Pieter Visser[1], Marc Naeije[1], Copernicus POD QWG team[2] | [1]Delft University of Technology, Delft, The Netherlands, [2]Copernicus POD QWG team			
7. Advances in Our Understanding of Land Processes and Inland Water Storage and Fluxes				
102	Global River Monitoring From Satellite Radar Altimetry-Achievements and Challenges	Philippa Berry	Roch Remote Sensing	UK
	Philippa Berry[1], Jerome Benveniste[2] | [1]Roch Remote Sensing, Roch, Haverfordwest, United Kingdom, [2]ESA-ESRIN, Largo Galileo Galilei, Frascati, Italy			
103	Constructing High-Frequency Time Series of Global Lake and Reservoir Storage Changes Using Landsat Imagery and Radar Altimetry	Fangfang Yao	Kansas State University	USA
	Fangfang Yao[1], Jida Wang[1], Chao Wang[2], Jean-François Crétaux[3] | [1]Kansas State University, Manhattan, United States, [2]University of Puerto Rico, San Juan, United States, [3]CNES , Toulouse, France			
104	HYDROWEB/HYSOPE : A Processing Center for Lakes and Rivers Observation	Jean-Francois Cretaux	CNES/LEGOS	FR
	Jean-Francois Cretaux[1], Stephane Calmant[2], Philippe Pacholczyk[3], Lionel Zawadzki[4], Joel Dorandeu[4], Valery Vuglinsky[5] | [1]CNES/LEGOS, Toulouse, France, [2]IRD/Legos, Toulouse, France, [3]CNES, Toulouse, France, [4]CLS, Ramonville St Agne, France, [5]SHI, St Petersburg, Russia			
105	Long-Term Chronicles of Fluvial Characteristics and Hydraulic Variables Using Multimission Satellite Altimetry in the Congo River Basin	Adrien Paris	CLS	FR
	Adrien Paris[1], Stéphane Calmant[2], Ayan Fleischmann[3], Taina Conchy[4], Vinicius Siqueira[3], Marielle Gosset[5], Rodrigo Cauduro Dias de Paiva[3], Walter Collischonn[3], Joecila Santos da Silva[4] | [1]Collecte Localisation Satellite (CLS), Ramonville, France, Ramonville Saint Agne, France, [2]LEGOS, Université de Toulouse, IRD, CNES, CNRS, UPS, Toulouse, France, [3]IPH, UFRGS, Porto Alegre, Brazil, [4]CESTU, UEA, Manaus, Brazil, [5]GET, Université de Toulouse, IRD, CNES, CNRS, UPS, Toulouse, France			

106	Ice Cover of Eurasian Lakes from Satellite and In-Situ Observations	Alexei Kouraev	LEGOS/Université de Toulouse/CNES/CNRS/IRD/ UPS Toulouse Tomsk State University	FR
	Alexei Kouraev[1,2], Elena Zakharova[3], Frédérique Rémy[1], Mikhail Shimaraev[4], Andrey Kostianoy[5], Andrey Suknev[6] | [1]LEGOS/Université de Toulouse/CNES/CNRS/IRD/UPS Toulouse, France, Toulouse, France, [2]Tomsk State University, Tomsk, Russia, [3]Water Problems Institute, Russian Academy of Sciences, Moscow, Russia, [4]Limnological Institute, Siberian Branch of Russian Academy of Sciences,Russia, [5]P.P Shirshov Institute of Oceanology RAS, Moscow, Russia, [6]Great Baikal Trail Buryatiya, Ulan-Ude, Russia			
107	HYDROLARE–Main Tasks and Activity	Valery Vuglinsky	SHI	RU
	Valery Vuglinsky[1], Jean-Francois Cretaux[2] | [1]SHI, St Petersburg, Russia, [2]CNES/LEGOS, Toulouse, France			
108	Challenges of Water Level Monitoring Over Narrow Rivers Using Multi-Mission Satellite Altimetry: Case Studies of Karun and Nile	Sajedeh Behnia	University of Stuttgart	DE
	Sajedeh Behnia[1], Nicolaas Sneeuw[1] | [1]Institute of Geodesy, University Of Stuttgart, Germany			
109	Assessment of Non-Stationary River Runoff in Boreal Catchments with Multi-Mission Altimetry	Elisabeth Woisetschläger	University of Stuttgart	DE
	beth Woisetschläger[1], Nico Sneeuw[1], Mohammad Tourian[1] | [1]Instiute of Geodesy, University of Stuttgart, Stuttgart, Germany			
110	Lake and River Water Level Measurements From Radar and ICESat Laser Altimetry and Comparisons With GRACE	Claudia Cristina Carabaja	Sigma Space Corp.	FR
	Claudia Cristina Carabajal[1], Jean-Paul Boy[2] | [1]Sigma Space Corp.@NASA/GSFC, Greenbelt, United States, [2]EOST-IPGS (UMR 7516), France			
111	Extending the Database of Hydrology Targets for DEM Onboard Altimeters	Denis Blumstein	CNES LEGOS	FR
	Denis Blumstein[1,2], Léa Lasson[2], Sylvain Biancamaria[2], Stéphane Calmant[2], Jean-François Crétaux[1,2], Muriel Bergé-Nguyen[1,2], Fabien Blarel[2], Frédéric Frappart[2], Fabrice Papa[2], Fernando Niño[2], Sara Fleury[2], Elena Zakharova[2], Sophie Le Gac[1], Nicolas Picot[1] | [1]CNES, Toulouse, France, [2]LEGOS, Toulouse, France			
112	Identification of the Rybinsk Reservoir Ice Cover and Investigation of its Interannual Variability Based on Satellite Altimetry and Radiometry	Sergey Lebedev	GC RAS Maykop State Technological University	RU
	Sergey Lebedev[1,2], Shamil Bogoutdinov[1], Pavel Kluev[3], Stanislav Nekhoroshev[1] | [1]GC RAS, Moscow, Russian Federation, [2]Maykop State Technological Institute, Maykop, Russian Federation, [3]Tver State University, Tver, Russian Federation			

113	G-REALM: Investigating the Jason-3 and Sentinel-3A Data Sets for the Next Phase of Operational Lake and Wetland Monitoring	Martina Ricko	SGT Inc NASA	USA
	Martina Ricko[1,2], Charon Birkett[3], Xu Yang[1], Brian Beckley[1,2], Curt Reynolds[4], Elias Deeb[5] | [1]SGT Inc, Greenbelt, USA, [2]NASA/GSFC, Greenbelt, USA, [3]ESSIC, University of Maryland, College Park, USA, [4]USDA/FAS, Washington, USA, [5]ERDC/USACE, Hanover, USA			
114	The SEOM "Sentinel-3 Hydrologic Altimetry Processor Prototype" (SHAPE) Project: Progresses & Status	Nicolas Bercher	Along-Track S.A.S	FR
	Nicolas Bercher[1], Dr. Pierre Fabry[1], Dr. Albert Garcia Mondejar[2], Dr Eduard Makhoul[8], Dr. Joana Fernandes[3], Dr. David Gustafsson[4], Dr. Marco Restano[5], Dr. Américo Ambrózio6, Dr. Jérôme Benveniste7 | [1]Along-Track S.A.S., Plougonvelin, France, [2]isardSAT UK, Surrey, United Kingdom, [3]University of Porto, Porto, Portugal, [4]SMHI, Norrköping, Sweden, [5]Serco, Frascati, Italy, [6]Deimos, Frascati, Italy, [7]ESA-ESRIN, Frascati, Italy, [8]isardSAT Spain, , Barcelona			
115	Validation of 25 Years of Altimetry Data over Inland Water: from T/P to Sentinel-3A	Nicolas Bercher	Along-Track S.A.S	FR
	Nicolas Bercher[1], Pierre Fabry[1] | [1]Along-Track S.A.S., Plougonvelin, France			
116	Selective Retracking of Bright Targets Exploiting Consecutive Waveforms: Application to LRM Altimetry Over Rivers	Nicolas Bercher	Along-Track S.A.S	FR
	Nicolas Bercher[1], Pierre Fabry[1], François Boy[2] | [1]Along-Track S.A.S, Plougonvelin, France, [2]CNES, Toulouse, France			
117	Monitoring Inland Water Bodies from Sentinel-3 and CryoSat-2 SAR Altimeters	Shirzad Roohi	University of Stuttgart	DE
	Shirzad Roohi[1] | [1]University of Stuttgart, Stuttgart, Germany			
118	Influence of the Recent Climatic Events on the Surface Water Storage of the Tonle Sap	Frédéric Frappart	GET | LEGOS	FR
	Frédéric Frappart[1,2], Sylvain Biancamaria[2], Cassandra Normandin[3], Fabien Blarel[2], Luc Bourrel[2], Aumont Mélanie[1,2], Azemar Pauline[1,2], Phuong Lan Vu[1], Thuy Le Toan[4], Bertrand Lubac[3], José Darrozes1 | [1]GET, Toulouse, France, [2]LEGOS, Toulouse, France, [3]EPOC, Bordeaux, France, [4]CESBIO, Toulouse, France			
119	Calibration and Validation of Inland Waters Heights from SAR, SARIN and Conventional Altimetry	Stuart Edwards	Newcastle University	UK
	Stuart Edwards[1], Philip Moore[1],Chirstopher Pearson[1] | [1]Newcastle University, Newcastle upon Tyne, United Kingdom			
120	Satellite Altimetry for Discharge Estimation and for Monitoring Extreme Events	Stefania Camici	IRPI-CNR	IT
	Stefania Camici[1], Angelica Tarpanelli[1] | [1]IRPI-CNR, Perugia, Italy			
121	Sentinel3 in the Context of Multisensor Synergy: New Discovery and Analysis Tools	Lucile Gaultier	OceanDataLab	FR
	Lucile Gaultier[1], Fabrice Collard[1], Gilles Guitton[1], Sylvain Herlédan[1], Ziad El Khoury Hanna[1], Guillaume Le Séach[1] | [1]OceanDataLab, Locmaria-Plouzané, France			

122	On the Potential of Altimetry Data for the Calibration of Hydraulic Models: a Comparison of Different Products and Multi-Mission Series	Alessio Domeneghetti	University of Bologna	IT

Alessio Domeneghetti[1], Giada Molari[1], Mohammad J. Tourian[2], Angelica Tarpanelli[3], Luca Brocca[3], Tommaso Moramarco[3], Attilio Castellarin[1], Nico Sneeuw[2], Armando Brath[1] | [1]University Of Bologna, Bologna, Italy, [2]Institute of Geodesy, University of Stuttgart, Stuttgart, Germany, [3]IRPI-CNR, Perugia, Italy

123	Evaluating the Use of River Level Estimations Derived From Radar Altimetry Data into Hydrological Modelling of the Chari River Basin	Mauro Arcorace	CIMA DIBRIS, University of Genoa	IT

Mauro Arcorace[1,2], Jérôme Benveniste[3], Giorgio Boni[1,2], Luca Dell'Oro[4], Simone Gabellani[1], Alessandro Masoero[1], Giovanni Sabatino[5], Olivier Sénégas[4], Francesco Silvestro[1] | [1]CIMA Research Foundation, Savona, Italy, [2]DIBRIS, University of Genoa, Genova, Italy, [3]ESA-ESRIN, Frascati, Italy, [4]UNITAR-UNOSAT, Geneva, Switzerland, [5]Progressive Systems srl c/o ESRIN, Frascati, Italy

124	Adaptation of the SAR Altimetric Ocean Retracker for Inland Waters: Methodology and Preliminary Results	Eduard Makhoul	IsardSAT	ES

Eduard Makhoul[1], Mònica Roca[1], Albert Garcia-Mondéjar[2], Qi Gao[1], Maria Jose Escorihuela[1] | [1]IsardSAT, Barcelona, Spain, [2]IsardSAT Ltd., Guildford, United Kingdom

125	Integrating Sentinel Series Data to Monitor Lake Level Variation in Tibet	Kuo-Hsin Tseng	NCU	TW

Kuo-Hsin Tseng[1,2], Aive Liibusk[3], C.K. Shum[4], Hyongki Lee[5], Chung-Yen Kuo[6] | [1]Center for Space and Remote Sensing Research, National Central University, Taoyuan, Taiwan, [2]Institute of Hydrological and Oceanic Sciences, National Central University, Taoyuan, Taiwan, [3]Department of Geomatics, Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Tartu, Estonia, [4]Division of Geodetic Science, School of Earth Sciences, Ohio State University, Columbus, United States, [5]Department of Civil and Environmental Engineering, University of Houston, Houston, United States, [6]Department of Geomatics, National Cheng Kung University, Tainan, Taiwan

126	Can Sentinel Measure Water Level over Po River at 80HZ?	Angelica Tarpanelli	IRPI-CNR	IT

Angelica Tarpanelli[1], Américo Ambrózio[2], Marco Restano[3], Jérôme Benveniste[4] | [1]IRPI-CNR, Perugia, Italy, [2]DEISMOS-ESRIN, Rome, Italy, [3]SERCO-ESRIN, Rome, Italy, [4]ESA-ESRIN, Frascati, Italy

127	Lake Bracciano Water Level Variation from Sentinel-3 Measurements Processed at the GPOD SARvatore Service	Marco Restano	SERCO	IT

Marco Restano[1], Salvatore Dinardo[2], Américo Ambrózio[3], Angelica Tarpanelli[4], Jérôme Benveniste[5] | [1]SERCO/ESA-ESRIN, Frascati, Italy, [2]He Space-EUMETSAT, Germany, [3]DEIMOS/ESA-ESRIN, Frascati, Italy, [4]CNR-IRPI, Perugia, Italy, [5]ESA-ESRIN, Frascati, Italy

8. Advances in Our Understanding of the Cryosphere				
128	25 Years of Radar Altimetry Over the Antarctic Ice Shelves: Retrieving Trends and Variability	Fernando Paolo	JPL	USA
	Fernando Paolo[1], Johan Nilsson[1], Alex Gardner[1] | [1]JPL, Pasadena, United States			
129	Pysiral–An Open Source Python Sea Ice Radar Altimetry Toolbox	Stefan Hendricks	Alfred-Wegener-Institut	DE
	Stefan Hendricks[1] | [1]Alfred-Wegener-Institut, Helmholtz Zentrum für Polar Und Meeresforschung, Bremerhaven, Germany			
130	Retrieving Sea Surface Topography in the Arctic Ocean from Satellite Altimetry with Ocean/Sea-Ice Processing Continuity	Pierre Prandi	CLS	FR
	Pierre Prandi[1], Poisson Jean-Christophe[1], Pierre Thibaut[1], Yannice Faugère[1] | [1]CLS, Ramonville Saint-agne, France			
131	Assessment of Sentinel-3 SAR Altimetry over Ice Sheets	Malcolm McMillan	University of Leeds	UK
	Malcolm McMillan[1], Alan Muir[2], Andrew Shepherd[1] | [1]University Of Leeds, Leeds, United Kingdom, [2]University College London, London, United Kingdom			
132	SAR Altimetry Processing Development for Ice Sheets	Malcolm McMillan	University of Leeds	UK
	Malcolm McMillan[1], Roger Escola[2], Monica Roca[2], Pierre Thibaut[3], Jeremie Aublanc[3], Frederique Remy[4], Andrew Shepherd[1], Marco Restano[5], Americo Ambrozio[5], Jerome Benveniste[5] | [1]University Of Leeds, Leeds, United Kingdom, [2]IsardSAT Ltd, Guildford, United Kingdom, [3]CLS, Ramonville Saint-Agne, France, [4]LEGOS, Toulouse, France, [5]ESA-ESRIN, Frascati, Italy			
133	Impact of Greenland Surface Melt on CryoSat-2 Elevation Measurements	Thomas Slater	University of Leeds	UK
	Thomas Slater[1], Andrew Shepherd[1], Malcolm McMillan[1], Thomas Armitage[2], Amber Leeson[3], Anna Hogg[1], Lin Gilbert[4], Alan Muir[4], Stephen Cornford[5], Kate Briggs[1] | [1]Centre for Polar Observation and Modelling, University Of Leeds, Leeds, United Kingdom, [2]JPL, California Institute of Technology, Pasadena, USA, [3]Lancaster Environment Centre/Data Science Institute, Lancaster University, Lancaster, United Kingdom, [4]Centre for Polar Observation and Modelling, University College London, London, United Kingdom, [5]Department of Geography, Swansea University, Swansea, United Kingdom			
134	A New Digital Elevation Model of Antarctica Derived from CryoSat-2 Altimetry	Thomas Slater	University of Leeds	UK
	Thomas Slater[1], Andrew Shepherd[1], Malcolm McMillan[1], Alan Muir[2], Lin Gilbert[2], Anna Hogg[1], Hannes Konrad[1,3], Tommaso Parrinello[4] | [1]Centre for Polar Observation and Modelling, University Of Leeds, Leeds, United Kingdom, [2]Centre for Polar Observation and Modelling, University College London, London, United Kingdom, [4]ESA-ESRIN, Frascati, Italy			
135	Techniques for Combining Multi-Mission Satellite Altimetry Time Series of Ice Sheet Elevation Change	Lin Gilbert	CPOM	UK
	Lin Gilbert[1], Alan Muir[1], Andrew Shepherd[1], Anna Hogg[1], Malcolm McMillan[1] | [1]CPOM, Leeds, United Kingdom			

136	Observation of the Ice Cover in the Okhotsk Sea by Dual-Frequency Precipitation Radar	Vladimir Karaev	Institute of Applied Physics Ras	RU
	Vladimir Karaev[1], Maria Panfilova[1], Eugeny Meshkov[1], Maria Ryabkova[1] | [1]Institute of Applied Physics Ras, Nizhny Novgorod, Russian Federation			
137	Inter-Comparison of AltiKa and CryoSat Over Greenland	Inès Otosaka	University of Leeds	UK
	Inès Otosaka[1], Andrew Shepherd1, Anna Hogg[1] | [1]School of Earth And Environment, University of Leeds, Leeds, United Kingdom			
138	Radar Altimetry to Support Ice Navigation	Eero Rinne	Finnish Meteorological Institute	FI
	Eero Rinne[1], Heidi Sallila[1], Markku Similä[1], Antti Kangas[1], Stefan Hendricks[2] | [1]Finnish Meteorological Institute, Helsinki, Finland, [2]Alfred Wegener Institute, Bremerhaven, Germany			
139	ERS-2, EnviSat, AltiKa: 23 Years of Repeat Radar Altimetry above the Antarctica Ice Sheet	Frédérique Rémy	CNRS	FR
	Frédérique Rémy[1], Fifi Adodo[1], Anthony Mémin[2] | [1]CNRS, Toulouse, France, [2]University Nice Sophia Antipolis, Nice, France			
140	Greenland CCI Surface Elevation Change Products from Cryosat-2 and SARAL/ALtiKa	Sebatian B. Simonsen	DTU Space	DK
	Sebatian B. Simonsen[1], Kirill Khvorostovsky[2], Louise Sandberg Sørensen[1], Rene Forsberg[1] | [1]Department Of Geodynamics, Dtu Space, Technical University Of Denmark, Kgs. Lyngby, Denmark, [2]Satellite Oceanography Laboratory, Russian State Hydrometeorological University, Saint Petersburg, Russia			
141	Satellite-Derived Sea-Ice Export and Its Impact on Arctic Ice Mass Balance	Robert Ricker	Alfred Wegener Institute	DE
	Robert Ricker[1], Fanny Girard-Ardhuin[2], Thomas Krumpen[1], Camille Lique[2] | [1]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, [2]University of Brest, CNRS, IRD, Ifremer,LOPS, IUEM, Brest, France			
142	Radar Wave Interaction with the Antarctica Snowpack: Outcomes of the ESA SPICE Project	Jeremie Aublanc	CLS	FR
	Jeremie Aublanc[1], Pierre Thibaut[1], Clément Lacrouts[1], Frédérique Rémy[2], Malcolm McMillan[3], Jérôme Benveniste[4] | [1]CLS, Ramonville-Saint-Agne, France, [2]LEGOS, Toulouse, France, [3]University of Leeds, Leeds, United Kingdom, [4]ESA, Frascati, Italy			
143	Validation of Satellite Cryosphere Altimetry with Airborne Surveys – Results of CryoVEx Campaigns	Sine M. Hvidegaard	DTU Space	DK
	Sine M. Hvidegaard[1], Henriette Skourup[1], René Forsberg[1], Taniâ Casal[2], Malcolm Davidson[2] | [1]DTU Space, Kgs. Lyngby, Denmark, [2]ESA, Noordvijk, The The Netherlands			
144	Topography of A68 Iceberg from Altika and Cryosat Data	Jean Tournadre	Ifremer	FR
	Jean Tournadre[1] | [1]Ifremer, Plouzané, France			

145	Quick Decisions–Choosing the Right Sea Ice Thickness Product	Heidi Sallila	Finnish Meteorological Institute	FI
	Heidi Sallila[1], Joshua McCurry[2], Sinéad Farrell[2], Eero Rinne[1] | [1]Finnish Meteorological Institute, Helsinki, Finland, [2]ESSIC, University of Maryland, College Park, USA			
146	A Synergistic Use of Sentinel-1 and CryoSat-2 SAR Data Over Sea Ice in the Cryo-SEANICE ESA Project	Pierre Fabry	Along-Track S.A.S.	FR
	Pierre Fabry[1], Moein Zohary[1], Nicolas Bercher[1], Jérôme Bouffard[2], Pierre Femenias[2] | [1]Along-Track S.A.S., Plougonvelin, France, [2]ESA-ESRIN, Frascati, Italy			
147	Looking Forward and Backward: New Techniques for Quantifying Dynamic Surface-Height Changes With Radar Altimetry in Antarctica	Matthew Siegfried	Stanford University	USA
	Matthew Siegfried[1], Dustin Schroeder[1], Davide Castelletti[1] | [1]Stanford University, Stanford, United States			
148	Toward a CryoSat-2 / Sentinel-3 Continuum of Sea-Ice Thickness and Volume Observations	Antoine Laforge	CTOH/LEGOS	FR
	Antoine Laforge[1], Sara Fleury[1], Kévin Guerreiro[1], Florence Birol[1], Salvatore Dinardo[2], Giovanni Sabatino[3], Jérôme Benveniste[3], Jérôme Bouffard[3], Pierre Féménias[3] [1]CTOH/LEGOS, Toulouse, France, [2]He Space-EUMETSAT, Darmstadt, Germany, [3]ESA-ESRIN, Frascati, Italy			
149	Consistent CryoSat-2 and Envisat Freeboard Retrieval of Arctic and Antarctic Sea Ice	Stephan Paul	Alfred Wegener Institute	DE
	Stephan Paul[1], Stefan Hendricks[1], Robert Ricker[1], Stefan Kern[2], Eero Rinne[3] | [1]Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany, [2]Integrated Climate Data Center, Hamburg, Germany, [3]Finnish Meteorological Institute, Helsinki, Finland			
150	Polar Ocean Case Study. An Example for Dedop Studio	Anna Bulczak	Isardsat	PL
	Anna Bulczak[1], Waldemar Walczowski[2] | [1]Isardsat, Gdansk, Poland, [2]Institute of Oceanology, Poland, Sopot, Poland			
151	Four Decades of Surface Elevation Change of the Antarctic Ice Sheet from Multi-Mission Satellite Altimetry	Ludwig Schröder	Technische Universität Dresden	DE
	Ludwig Schröder[1], Martin Horwath[1], Reinhard Dietrich[1], Veit Helm[2] | [1]Technische Universität Dresden, Institut Für Planetare Geodäsie, Dresden, Germany, [2]Alfred Wegener Institute Helmholtz, Centre for Polar and Marine Research, Bremerhaven, Germany			
152	CryoSat: ESA'S Ice Explorer Mission, 8 Years in Operations: Status, Main Achievements and Future Outlook	Tommaso Parrinello	ESA	IT
	Tommaso Parrinello[1] | [1]ESA-ESRIN, Frascati, Italy			

153	Sea Ice Mass Reconciliation Exercise (SIMRE) for Altimetry Based Sea Ice Thickness Data Sets	Stefan Hendricks	Alfred-Wegener-Institut	DE

Stefan Hendricks[1], Christian Haas[1], Michel Tsamados[2], Andy Ridout, Ron Kwok[4], Nathan Kurtz[5], Kévin Guerreiro[6], Eero Rinne[7], Anna Bulczak[8]
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154	Towards a Multi-Decadal Pan-Arctic Snow Depth on Sea Ice: A Novel Model-Satellite-Airborne Fusion Approach	Isobel Lawrence	University College London	UK

Isobel Lawrence[1], Michel Tsamados[1], Sammie Buzzard[1], Harry Heorton[1], Andy Ridout[1], Julienne Stroeve[1] | [1]University College London, London, United Kingdom

155	Estimating Time-Variable Basal Melt Rates of Antarctic Ice Shelves: Progress and Challenges	Susheel Adusumilli	Scripps Institution of Oceanography	USA

Susheel Adusumilli[1], Helen Amanda Fricker[1], Laurie Padman[2] | [1]Scripps Institution Of Oceanography, La Jolla, USA, [2]Earth and Space Research, Corvallis, United States

156	Monitoring Measurement Performance Of The CryoSat SIRAL Level 2 Data Products	Julia Gaudelli	UCL	UK

Julia Gaudelli[1], Steven Baker[1], Alan Muir[1], David Brockley[1] | [1]UCL, Dorking, United Kingdom

157	Radar vs LiDAR: Where Are Their Reflective Surfaces in Vegetation and Ice/Snow?	Alexander Braun	Queen's University | WLS	CA/FI

Alexander Braun[1,2], Christian Ginzler[2], Yves Buehler[2] | [1]Queen's University, Kingston, Canada, [2]Swiss Federal Institute for Forest, Snow and Landscape Research, WSL, Birmensdorf, Switzerland

158	Results from the ESA Arctic+ Snow Project	Michel Tsamados	University College London	UK

Michel Tsamados[1], Samantha Buzzard[1], Isobel Lawrence[1], Julienne Stroeve[1], Christian Haas[2,3], Steffan Hendricks, Eero Rinne[5], Thomas Armitage[4], Anna Bulczak[6], Andrew Ridout[1] | [1]Centre for Polar Observation and Modelling, University College London, London, United Kingdom, [2]Alfred Wegener Institut, Bremerhaven, Germany, [3]York University, York, Canada, [4]NASA JPL,United States, [5]Finnish Meteorological Institute, Helsinki, Finland, [6]IsardSAT Poland, Gdynia, Poland

159	Multi-Decadal Arctic Sea Ice Roughness	Michel Tsamados	University College London	UK

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160	25 Year Time Series of Multiple-Satellite Ice Sheet Changes: the ESA Climate Change Initiative	Rene Forsberg	DTU Space	DK
	Rene Forsberg[1], Louise Sorensen[1], Sebastian Simonsen[1], Valentina Barletta[1], Anders Kusk[1], Thomas Nagler[2], Markus Hetzenecker[2], Andy Shepherd[3], Andreas Groh[4], Anne Solgaard[5], Marcus Engdahl[6] | 1DTU Space, Lyngby, Denmark, [2]ENVEO, Innsbruck, Austria, [3]University of Leeds, Leeds, UK, [4]Technical University of Dresden, Dresden, Germany, [5]GEUS, Copenhagen, Denmark, [6]ESA-ESRIN, Frascati, Italy			
161	Assessing Stability and Precision of Sea-Ice Thickness Retrievals from Satellite Altimetry by a Cross-over Analysis	Robert Ricker	AWI	DE
	Robert Ricker[1], Stefan Hendricks[1], Stephan Paul[1] | [1]AWI, Bremerhaven, Germany			
162	Sensitivity Analysis of Different Processing Approaches on Ice-Volume Change Estimates of Greenland and Antarctica	Veit Helm	Alfred Wegener Institute	DE
	Veit Helm[1], Angelika Humbert[1,2] | [1]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, [2]University of Bremen, Bremen, Germany			
163	Snow Depth on Sea Ice for 2013-2017 Arctic Winters from CryoSat-2 and SARAL Inter-Comparison	Sara Fleury	LEGOS/CTOH	FR
	Sara Fleury[1], Kévin Guerreiro[1], Antoine Laforge[1], Florence Birol[1], François Boy[2], Amandine Guillot[2], Nicolas Picot[2], Pierre Thibaut[4], Jérôme Bouffart[3], Pierre Féménias[3], Tommaso Parinello[3] | [1]LEGOS/CTOH, Toulouse, France, [2]CNES, Toulouse, France, [3]ESA-ESRIN, Frascati, Italy, [4]CLS, Toulouse, France			
164	Changes in Antarctic Ice Sheet Surface Elevation from a Quarter-century of Combined Radar and Laser Altimetry	Johan Nilsson	NASA	USA
	Johan Nilsson[1], Fernando Paolo[1], Alex Gardner[1], Sebastian Bjerregaard Simonsen[2] | [1]JPL-NASA, California Institute of Technology, Pasadena, United States, [2]DTU Space, National Space Institute, Technical University of Denmark, Kgs. Lyngby, Denmark			
165	Sea Ice Freeboard from ICESat-2 Multi-Beam Altimetry	Thomas Armitage	JPL	USA
	Ron Kwok[1], Thomas Armitage[1] | [1]JPL, Pasadena, United States			
166	Towards an Operational Snow Depth and Density Product for use in Radar Altimetry	Julienne Stroeve	University College London	UKA
	Julienne Stroeve[1], Glen Liston[1], Samantha Buzzard[1], Michel Tsamados[1] | [1]University College London, London, United Kingdom			

9. Extending the 25-Year Altimetric Record: Challenges and Achievements

167	Use of Satellite Altimeter Data for Comparison and Calibration of Century Based Wind and Wave Climate Data Record	Berguzar Oztunali Ozbahceci	Izmir Institute of Technology	TR
	Berguzar Oztunali Ozbahceci[1], Ahmet Rıza Turgut[1], Ahmet Bozoklu[1], Dr Saleh Abdalla[2] | [1]Izmir Institute Of Technology, Izmir, Turkey, 2ECMWF, Reading, UK			
168	Corsica: A 20-yr Multi-Mission Absolute Altimeter Calibration Site	Pascal Bonnefond	SYRTE	FR
	Pascal Bonnefond[1], Pierre Exertier[2], Olivier Laurain[2], Thierry Guinle[3], Pierre Féménias[4] | [1]Observatoire de Paris-SYRTE, Paris, France, [2]OCA/Geoazur, Sophia-Antipolis, France, [3]CNES, Toulouse, France, [4]ESA-ESRIN, Frascati, Italy			
169	Updates to the Geosat 30th Anniversary Data Set	Eric Leuliette	NOAA	US
	Eric Leuliette[1], Walter H. F. Smith[1], Remko Scharroo[2], Frank Lemoine[3], Nikita Zelensky[4], John Lillibridge | [1]NOAA, College Park, United States, [2]EUMETSAT, Darmstadt, Germany, [3]NASA Goddard Space Flight Center, Greenbelt, United States, [4]SGT Inc., Greenbelt, United States			
170	Saral/Altika Altimetry Data Processing for Determination of the Mean Sea Surface over the Western Mediterranean Sea	Touati Benkouider	Centre Of Space Techniques	DZ
	Touati Benkouider[1], Ali Rami[1] | [1]Centre Of Space Techniques, Arzew, Algeria			
171	Estimating Trend Uncertainties of Global Mean Sea level Evolution over the 25-Year Altimetry Era	Michaël Ablain	CLS	FR
	Michaël Ablain[1], Zawadzki Lionel[1], Rémi Jugier[1], Benoit Meyssignac[2], Anny Cazenave[2] | [1]CLS, Ramonville Saint-Agne, France, [2]LEGOS, Toulouse, France			
172	Calibration and Intercalibration of the ERS-1/ERS-2/Envisat Microwave Radiometer Time Series: ESA's MWR EMiR Project	Ralf Bennartz	Vanderbilt University University of Wisconsin	USA
	Ralf Bennartz[1,2], Frank Fell[3], Bruno Picard[4], Stefano Casadio[5], Martin Stengel[6], Marc Schröder[6], Bojan Bojkov[7], Pierre Féménias[5] | [1]Vanderbilt University, Nashville, United States, [2]University of Wisconsin, Madison, United States, [3]Informus GmbH, Berlin, Germany, [4]CLS, Toulouse, France, [5]ESA-ESRIN, Frascati, Italy, [6]German Meteorological Service, Offenbach, Germany, [7]EUMETSAT, Darmstadt, Germany			
173	Developing Long-Term Consistent Altimeter Datasets for the Sentinel Era	Graham Quartly	Plymouth Marine Laboratory	UK
	Graham Quartly[1], Francesco Nencioli[1], Sylvie Labroue[2], Pierre Femenias[3], Remko Scharroo[4], Marie-Laure Frery[2], Saleh Abdalla[5], Matthias Raynal[2], Pablo Garcia[6], Albert Garcia[6], Alan Muir[7] | [1]Plymouth Marine Laboratory, Plymouth, UK, [2]CLS, Toulouse, France, [3]ESA-ESRIN, Frascati, Italy, [4]EUMETSAT, Darmstadt, Germany, [5]ECMWF, Reading, UK, [6]IsardSAT, Barcelona, Spain, [7]University College London, London, UK			
174	CryoSat Precise Orbit and Long Term Ocean Data Analysis and Validation	Marc Naeije	TU Delft	NL
	Marc Naeije[1], Ernst Schrama[1] | [1]TU Delft / Space Engineering, Delft, The Netherlands			

175	CryoSat-2 Range, Datation and Interferometer Calibration with Transponders	Albert Garcia-Mondejar	Isardsat Ltd	UK
	Albert Garcia-Mondejar[1], Marco Fornari[2], Stelios Mertikas[3], Jerome Bouffard[4], Joe Wood1, Pierre Féménias[5], Mònica Roca[1] | [1]Isardsat Ltd., Guildford, United Kingdom, [2]ESA-ESTEC, , The Netherlands, [3]Technical University of Crete, Greece, [4]RHEA–System c/o ESA-ESRIN, Frascati, Italy, [5]ESA-ESRIN, Frascati, Italy			
176	From Conventional to High Resolution Delay Doppler Altimetry:a Review of the Altimeters Performances over Ocean	Matthias Rayna	CLS	FR
	Matthias Raynal[1], Sylvie Labroue[1], Thomas Moreau[1], François Boy[2], Nicolas Picot[2], Salvatore Dinardo[3], Pierre Féménias[4], Jérôme Bouffard[4], Jérôme Benveniste[4] [1]CLS, Toulouse, France, [2]CNES, Toulouse, France, [3]EUMETSAT, Darmstadt, Germany, [4]ESA-ESRIN, Frascati, Italy			
177	Tropospheric Corrections for Satellite Altimetry: Main Achievements and Perspectives	Joana Fernandes	Universidade Do Porto CIIMAR	PR
	Joana Fernandes[1],[2], Clara Lázaro[1],[2] | [1]Universidade Do Porto-Faculdade De Ciências, Porto, Portugal, [2]CIIMAR, Matosinhos, Portugal			
178	Evaluation of Delay-Doppler SAR Processing Algorithms Over Open Ocean	Eduard Makhoul	Isardsat	ES
	Eduard Makhoul[1], Mònica Roca[1], Chris Ray[1],[2], Roger Escolà[1], Gorka Moyano[1], Albert Garcia-Mondéjar[1], David Cotton[3], Marco Restano[4] | [1]Isardsat, Barcelona, Spain, [2]Saint Mary's College of California, Moraga, United States, [3]SatOC, Bramhall, United Kingdom, [4]SERCO c/o ESA, Rome, Italy			
179	The Permanent Facility for Satellite Altimetry Calibration in Gavdos/Crete, Greece: Fifteen years of Cal/Val Service	Stelios Mertikas	Technical University of Crete	GR
	Stelios Mertikas[1], Craig Donlon[2], Pierre Féménias[3], Demitris Galanakis[4], Achilles Tripolitsiotis[4], Xenophon Frantzis[1] | [1]Technical University of Crete, Chania, Crete, Greece, [2]ESA-ESTEC, Noordwijk, Netherland, [3]ESA-ESRIN, Frascati, Itally, [4]Space Geomatica P.C., Chania, Greece			
180	International Standardization for Satellite Altimetry Calibration: Lessons from the Past and Roadmap to the Future	Stelios Mertikas	Technical University of Crete	GR
	Pablo Garcia[1] | [1]isardSAT SL, Barcelona, Spain			
181	The Sentinel-3 SRAL Instrumental Calibration Monitoring.	Pablo Garcia	IsardSAT	ES
	Kévin Guereiro[1], Sara Fleury[1], Antoine Laforge[1], Benoit Meyssignac[1] | [1]LEGOS–CNRS, UMR5566, Toulouse, France			
182	Monitoring Long Term Variations of Arctic Sea Ice Thickness Using Several Satellite Altimetry Missions	Kévin Guereiro	LEGOS–CNRS	FR
	Albert Garcia-Mondejar[1], Stelios Mertikas[2], Demitris Galanakis[2], Sylvie Labroue, Jérôme Bruniquel[6], Graham Quartly[7], Pierre Féménias[4], Constantin Mavrocordatos[5], Pablo García[1], Mònica Roca[1] | [1]IsardSAT SL, Barcelona, Spain, [2]Technical University of Crete, Greece, [3]CLS, Toulouse, France, [4]ESA-ESRIN, Frascati, Italy, [5]ESA-ESTEC, Noordwijk, The Netherlands, [6]ACRI-ST, Sophia-Antipolis, France, [7]Plymouth Marine Laboratory, Plymouth, United Kingdom			

183	Sentinel-3 Range and Datation Calibration with Crete Transponder	Albert Garcia-Mondejar	IsardSAT	ES
	Zhongxiang Zhao[1], Peter Rhines[2] | [1]Applied Physics Laboratory, University Of Washington, Seattle, United States, [2]School of Oceanography, University of Washington, Seattle, United States			
184	Internal Tide Oceanic Tomography	Zhongxiang Zhao	University of Washington	USA
	David Brockley[1] | [1]Mullard Space Science Lab, Holmbury St Mary, United Kingdom			
185	The Democratisation of Satellite Data Processing	David Brockley	Mullard Space Science Lab	UK
	Stefano Vignudelli[1], Francesco De Biasio[2], Andrea Scozzari[3], Stefano Zecchetto[2] | [1]CNR-IBF, Pisa, Italy, [2]CNR-ISAC, Padova, Italy, [3]CNR-ISTI, Italy			
186	Revisiting Sea Level Trends Around Venice Using Tide Gauge Records and Improved Satellite-Based Sea Level Products from ESA CCI Project	Stefano Vignudelli	CNR-IBF	IT
	Stefano Vignudelli[1], Francesco De Biasio[2], Andrea Scozzari[3], Stefano Zecchetto[2] | [1]CNR-IBF, Pisa, Italy, [2]CNR-ISAC, Padova, Italy, [3]CNR-ISTI, Italy			
187	25 Years of Wet Tropospheric Correction: Short-Term Error Assessment by Comparison to Radiosondes	Marie-Laure Frery	CLS	FR
	Marie-Laure Frery[1], Bruno Picard[1], Mathilde Siméon[1], Christophe Goldstein[2], Pierre Féménias[3], Remko Scharroo[4] | [1]CLS, Ramonville Saint-Agne, France, [2]CNES, Toulouse, France, [3]ESA-ESRIN, Frascati, Italy, [4]Eumetsat, Darmstadt, Germany			
188	Comparison of Linear and Nonlinear Impact to Sea Level Variability Based on Satellite Data	Tatyana Belonenko	Saint Petersburg State University	RU
	Tatyana Belonenko[1], Nikita Sandaliuk[1] | [1]Saint Petersburg State University, Saint Petersburg, Russian Federation			
189	Validation of Coastal Sea Level Altimetry Data at High Posting Rate:80 Hz, from Sentinel-3A SRAL	Ana I Aldarias	University of Cadiz	ES
	Ana I Aldarias[1], Jesús Gómez-Enri[1], Irene Laiz[1], Begoña Tejedor[1], Stefano Vignudelli[2], Paolo Cipollini[3] | [1]University of Cadiz, Puerto Real, Spain, [2]Institute of Biophysics, CNR, Pisa, Italy, [3]ESA Climate Office, Oxfordshire, United Kingdom			
190	Lessons Learned After 10 Years of Validation of Coastal Altimetry Products in the Gulf of Cadiz and the Srait of Gibraltar (Southwestern Iberian Peninsula)	Jesus Gomez-Enri	University of Cadiz	ES
	Jesus Gomez-Enri[1], Ana Aldarias1, Stefano Vignudelli[2], Paolo Cipollini[3], Irene Laiz[1], Marcello Passaro[4], Begoña Tejedor[1] | [1]University Of Cadiz, Puerto Real, Spain, [2]Istituto di Biofisica, CNR, Pisa, Italy, [3]ESA Climate Office, Oxfordshire, U.K., [4]Deutsches Geodätisches Forschungsinstitut TUM, Munich, Germany			

191	Contribution of 25 Years of Radar Altimeter Climate Data Record Towards Quantifying Global Geocentric Sea-Level Rise Over the Past Seven Decades	C.K. Shum	Ohio State University CAS	US

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192	Monitoring Topography of Intertidal Zones Using Satellite Radar Altimetry	Frédéric Frappart	GET | LEGOS	FR

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193	Sea level Change since 2005: Importance of Salinity	William Llovel	CNRS-LEGOS	FR

William Llovel[1], Sarah Purkey[2], Benoit Meyssignac[1], Nicolas Kolodziejczyk[3], Alejandro Blazquez[1], Jonathan Bamber[4] | [1]CNRS-LEGOS, Toulouse, France, [2]Scripps Institution of Oceanography, University of California San Diego, La Jolla, United States, [3]LOPS-CNRS, Brest, France, [4]University of Bristol, Bristol, United Kingdom

194	Arctic Freshwater Fluxes from Satellite Altimetry and Earth Observation Data	Ole Baltazar Andersen	DTU Space	DK

Ole Baltazar Andersen[1], Karina Nielsen[1], Henriette Skourup[1], Louise Sandberg Sørensen[1], Thomas Nagler[2], Jan Vuite[2], Alecei Kouraev[3], Eena Zakharova[3], Diego Fernandez[4] | [1]DTU Space, Kongens Lyngby, Denmark, [2]ENVEO, Austria, [3]LEGOS, France, [4]ESA-ESRIN, Frascati, Italy

195	Final Results from GOCE++ Dynamical Coastal Topography and Tide Gauge Unification Using Altimetry and GOCE	Ole Baltazar Andersen	DTU Space	DK

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196	A New OGMOC Mean Dynamic Topography Model–DTU17MDT	Per Knudsen	DTU Space	DK

Per Knudsen[1], Ole B Andersen[1], Thomas Fecher[2], Thomas Gruber[2], Nikolai Maximenko[3] | [1]DTU Space, Kongens Lyngby, Denmark, [2]Institute of Astronomical and Physical Geodesy, TUM, Germany, [3]University of Hawaii at Manoa, IPRC, Honolulu, USA

197	A Combined Mean Dynamic Topography Model–DTU17cMDT	Per Knudsen	DTU Space	DK

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198	Seamless Transition from LRM to SAR in the Arctic Ocean	Stine Kildegaard Rose	DTU Space	DK

Stine Kildegaard Rose[1], Ole Baltazar Andersen[1], Carsten Ludwigsen[1] | [1]DTU Space, Kongens. Lyngby, Denmark

199	Sea Level Anomalies and Mesoscale Activity Using Altimetry Along the African Coats in the Eastern Tropical Atlantic Ocean (OSTST Alti-ETAO Project)	Habib Boubacar Dieng	LEGOS	FR
	Habib Boubacar Dieng[1], Isabelle Dadou[1], Fabien Léger[1], Florence Birol[1], Florent Lyard[1], Yves Morel[1], Alexis Chaigneau[1,2] | [1]LEGOS,Toulouse, France, [2]IRHOB/CIPMA, Cotonou, Benin			
200	CryoSat Interferometer Performance After 8 Years in Orbit	Michele Scagliola	Aresys Srl	IT
	Michele Scagliola[1], Marco Fornari[2], Jerome Bouffard[3], Tommaso Parrinello[3] | [1]Aresys Srl, Milan, Italy, [2]ESA-ESTEC, Noordwijk, The Netherlands, [3]ESA-ESRIN, Frascati, Italy			
201	CryoSat SIRAL: Instrument Performance After 8 Years of Operations	Michele Scagliola	Aresys Srl	IT
	Michele Scagliola[1], Marco Fornari[2], Jerome Bouffard[3], Tommaso Parrinello[3] | [1]Aresys Srl, Milan, Italy, [2]ESA-ESTEC, Noordwijk, The Netherlands, [3]ESA-ESRIN, Frascati, Italy			
202	A Validation Dataset For CryoSat Sea Ice Investigators	Julia Gaudelli	UCL	UK
	Julia Gaudelli[1] | [1]UCL, Dorking, United Kingdom			
203	How GNSS IPPP Positioning Technique Can Help Space Altimeter Missions?	Felix Perosanz	CNES-GET	FR
	Felix Perosanz[1], Daniel Moreira[2], Georgia Katsigianni[1], Sylvain Loyer[3], Flavien Mercier[1], Jean-Francois Cretaux[4], Stéphane Calmant[4], Muriel Bergé[4], Jean-Charles Marty[1] | [1]Cnes-GET, Toulouse, France, [2]CPRM, Rio de Janeiro, Brazil, [3]CLS, Ramonville, France, [4]LEGOS-CNES, Toulouse, France			
204	Developments in Sentinel-3 Altimetry for Sea Ice	Steven Baker	UCL-MSSL	UK
	Steven Baker[1], David Brockley[1], Alan Muir[1], Julia Gaudelli[1] | [1]UCL-MSSL, Dorking, Surrey, United Kingdo			
205	25 years of Caspian Sea Level Fluctuations and its Regional Variability	Saskia Esselborn	GFZ	DE
	Saskia Esselborn[1], Tilo Schöne[1] | [1]GFZ German Research Centre for Geosciences, Potsdam, Germany			
206	Vertical Land Motion Determined by Satellite Altimetry and Tide-Gauge Data in Fennoscandia	Martina Idzanovic	NMBU	NO
	Martina Idzanovic[1], Kristian Breili[2,1], Christian Gerlach[3,1], Ole Baltazar Andersen[4] | [1]Faculty of Science and Technology, NMBU, Ås, Norway, [2]Geodetic Institute, Norwegian Mapping Authority, Hønefoss, Norway, [3]Research Group for Geodesy and Glaciology, BAdW, Munich, Germany, [4]DTU Space, Technical University of Denmark, Lyngby, Denmark			

10. Synergy Between Altimetry, Other Data and Models in Support of Operational Oceanography

207	Impact of the Assimilation of High-Resolution and High-Frequency Data in a Regional Model	Mounir Benkiran	Mercator-océan	FR
	Mounir Benkiran[1], Elisabeth Rémy[1], Jean-Michel Lellouche[1], Marie-isabelle Pujol[2] | [1]Mercator-océan, Ramonville St-agne, France, [2]CLS, Ramonville St-agne, France			
208	The Multi Observation Thematic Assembly Centre of the Copernicus Marine Environment Monitoring Service	Marie-Helene Rio	CLS	FR
	Stephanie Guinehut[1], Bruno Buongiorno Nardelli[2], Herve Claustre[3], Riccardo Droghei[2], Helene Etienne[1], Marion Gehlen[4], Eric Greiner[1], Sandrine Mulet[1], Marie-Helene Rio[1], Nathalie Verbrugge[1] | [1]CLS, Ramonville Saint-Agne, France, [2]CNR, Roma, Italy, [3]Laboratoire d'Océanographie de Villefranche, Observatoire Océanologique de Villefranche, CNRS-INSU, Sorbonne Universités, UPMC University Paris 06, Villefranche-Sur-Mer, France, [4]Laboratoire des Sciences du Climat et de l'Environnement, Institut Pierre-Simon Laplace, CEA-CNRS-UVSQ, Gif sur Yvette Cedex, France			
209	Tailored Altimeter Products for Assimilation Systems (TAPAS products)	Marie Isabelle Pujol	CLS	FR
	Marie Isabelle Pujol[1], Yannice Faugère[1], Mounir Benkiran[2], Gérald Dibarboure[3] | [1]CLS, Ramonville, France, [2]Mercator Ocean, Ramonville, France, [3]CNES, Toulouse, France			
210	An OSSE to Quantify the Reliability and the Accuracy of Automatic Eddy Detection Performed on Gridded Altimetric Product	Alex Stegner	CNRS	FR
	Alex Stegner[1], Briac LeVu[1], Elodie Charles[2], Yannice Faugere[2] | [1]CNRS, Ecole Polytechnique, Palaiseau, France, [2]CLS, Toulouse, France			
211	Coastal Currents In The Eastern Gulf of Tehuantepec, Mexico	Armando Trasviña-Castro	CICESE	MX
	Armando Trasviña-Castro[1], Juan Pablo Salazar-Ceciliano[2], Eduardo Gonzalez-Rodriguez[1] | [1]CICESE, Unidad La Paz, La Paz, Mexico, [2]Departamento de Física, Universidad Nacional de Costa Rica, Heredia, Costa Rica			
212	On the Use of Eddies Detected from Surface Drifters to Quantitatively Validate and Compare the Mesoscale Eddy Atlases Constructed from Altimetry Maps	Rémi Laxenaire	Laboratoire de Météorologie Dynamique	FR
	Rémi Laxenaire[1], Sabrina Speich[1], Alexandre Stegner[1] | [1]Laboratoire de Météorologie Dynamique, UMR 8539 Ecole Polytechnique, ENS, CNRS, Paris, France			
213	In Situ and Satellite Altimetry Ocean Currents in a Biologically Productive Region of the Patagonia Continental Shelf, Argentina	Loreley Selene Lago	INIDEP FCEN Universidad de Buenos Aires UMI-IFAECI/CNRS-CONICET-UBA	AR
	Loreley Selene Lago[1,2,3], Harold Fenco[1], Patricia Martos[1,4], Raul Guerrero[1], Alberto Piola[2,5], Christine Provost[6], Martin Saraceno[2,3,7] | [1]INIDEP, Mar Del Plata, Argentina, 2DCAO, FCEN Universidad de Buenos Aires, Buenos Aires, Argentina, [3]UMI-IFAECI/CNRS-CONICET-UBA, Buenos Aires, Argentina, [4]FCEyN, Universidad Nacional de Mar del Plata, Mar del Plata, Argentina, [5]Departamento de Oceanografía, SHN, Buenos Aires, Argentina, [6]Laboratoire d'Océanographie et du Climat: Experimentation et Approches Numériques, UMR 7159, Paris, France, [7]CIMA-CONICET/UBA, Buenos Aires, Argentina			

214	Synergy between HF Radar and Altimetry in the SE Bay of Biscay	Ivan Manso	AZTI	ES
	Ivan Manso[1], Ainhoa Caballero[1], Anna Rubio[1], Claire Dufau[2], Florence Birol[3] | [1]AZTI, Pasaia, Spain, [2]CLS, Ramonville St. Agne, France, [3]LEGOS, Toulouse, France			
215	On the Approximation of the Inverse Error Covariances of High Resolution Satellite Altimetry Data	Joseph D'Addezio	University of Southern Mississippi	USA
	Joseph D'Addezio[1], Max Yaremchuk[2], Gleb Panteleev[2], Gregg Jacobs[2] | [1]University of Southern Mississippi, Hattiesburg, United States, [2]Naval Research Laboratory, Stennis Space Center, United States			
216	Study of a Mesoscale Eddy Using Drifters and Coastal Altimetry in the Bay of La Paz, Mexico	Maria Yesenia Torres Hernandez	CICIMAR-IPN	MX
	Maria Yesenia Torres Hernandez[1], Alida Rosina Rosales Villa[2], Armando Trasviña Castro[3] | [1]CICIMAR-IPN, La Paz, Mexico, [2]CICIMAR-IPN , La Paz, México, [3]CICESE Unidad La Paz, La Paz, Mexico			
217	CryoSat-2 On-going Cal/Val and Oceanographic Studies from Pole to Equator	Chris Banks	National Oceanography Centre	UK
	Chris Banks[1], Francisco Mir Calafat[1], Paolo Cipollini[5], Helen Snaith[3], Christine Gommenginger[2], Nadim Dayoub[2], Andrew Shaw[4], Jérôme Bouffard[6], Pierre Féménias[7] [1]National Oceanography Centre, Liverpool, United Kingdom, [2]National Oceanography Centre, Southampton, United Kingdom, [3]British Oceanographic Data Centre, Southampton, United Kingdom, [4]SKYMAT Ltd., Southampton, United Kingdom, [5]Telespazio Vega UK for ESA Climate Office - ECSAT, Harwell, United Kingdom, [6]RHEA-ESA, Frascati, Italy, 7ESA-ESRIN, Frascati, Italy			
218	Malvinas Current at 44.7ºS: Analysis of its Variability from in-situ Data and 25 years of Satellite Altimetry Data	Guillermina F. Paniagua	CIMA-CONICET/UBA Universidad de Buenos Aires UMI-IFAECI/CNRS-CONICET-UBA	AR
	Guillermina F. Paniagua[1,2,3], Martín Saraceno[1,2,3], Ramiro Ferrari[1,3], Loreley Lago[2,3,4], Camila Artana[6], Alberto R. Piola[2,3,5], Raúl Guerrero[4] | [1]CIMA-CONICET/UBA, Buenos Aires, Argentina, [2]Departamento de Ciencias de la Atmósfera y de los Océanos, FCEN, Universidad de Buenos Aires, Buenos Aires, Argentina, [3]UMI-IFAECI/CNRS-CONICET-UBA, Buenos Aires, Argentina, [4]Instituto Nacional de Investigación y Desarrollo Pesquero, Mar del Plata, Argentina, [5]Departamento de Oceanografía, SHN, Buenos Aires, Argentina, [6]Laboratoire d'Océanographie et du Climat: Experimentation et Approches Numériques, UMR 7159, Paris, France			
219	Effect of Altimeter Data Assimilation on the Ecosystem Distributions in the Japan Sea	Katsumi Takayama	Kyushu University	JP
	Katsumi Takayama[1], Naoki Hirose[1] | [1]Research Institute For Applied Mechanics, Kyushu University, Kasuga, Japan			
220	Altimeter Assimilation with Offline Estimates of Non-Steric Sea Surface Height Variations	Norihisa Usui	Meteorological Research Institute	JP
	Norihisa Usui[1], Takahiro Toyoda[1], Tsurane Kuragano[1,2], Nariaki Hirose[1], Yosuke Fujii[1], Hiroyuki Tsujino[1] | [1]Meteorological Research Institute, Tsukuba, Japan, 2Tokyo University of Science, Tokyo, Japan			

221	Impact of Assimilated Altimetric Observations in the Mercator Océan Forecasting System	Mathieu Hamon	Mercator Océan	FR
	Mathieu Hamon[1], Elisabeth Remy[1], Matthieu Clavier[1], Drillet Yann[1] | [1]Mercator Océan, Ramonville-Saint-agne, France			
222	Detection of Ships Using Sentinel-3A SRAL Altimeter Waveforms	Jesus Gomez-Enri	University of Cadiz	ES
	Jesus Gomez-Enri[1], Roberto Mulero[1], Stefano Vignudelli[2], Andrea Scozzari[3] | [1]University Of Cadiz, Puerto Real, Spain, [2]CNR, Pisa, Italy, [3]Institute of Information Science and Technologies-CNR, Pisa, Italy			
223	Monitoring the Algerian Basin Through Glider Observations, Satellite Altimetry and Numerical Simulations During the ABACUS Projects (2014-2018)	Giuseppe Aulicino	Università Politecnica Delle Marche Università degli Studi di Napoli Parthenope	IT
	Giuseppe Aulicino[1,2], Yuri Cotroneo[2], Simon Ruiz[3], Ananda Pascual[3], Antonio Sanchez Roman[3], Giannetta Fusco[2], Marc Torner[3], Emma Heslop[4], Giorgio Budillon[2], Joaquin Tintoré[3,4] | [1]Università Politecnica Delle Marche, Ancona, Italy, [2]Università degli Studi di Napoli Parthenope, Napoli, Italy, [3]IMEDEA (CSIC-UIB), Esporles, Spain, [4]SOCIB, Palma de Mallorca, Spain			
224	Reconstruction of the West Spitsbergen Current Using a Combination of Observations from Satellite Altimetry, Numerical Model and In Situ	Anna Bulczak	IsardSat	PL
	Anna Bulczak[1], Prof Waldemar Walczowski[2] | [1]IsardSat, Gdansk, Poland, [2]Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland			
225	Impact of a New High Resolution Mean Dynamic Topography and its Associated Error on the Assimilation of Sea Level Anomaly Altimetry Data in Mercator Ocean Reanalyses at ¼° and 1/12°	Jean-Michel Lellouche	Mercator Ocean	FR
	Jean-Michel Lellouche1, Eric Greiner[2] | [1]Mercator Ocean, Ramonville Saint Agne, France, [2]CLS, Ramonville Saint Agne, France			
226	New Connections Across the Ecosystem Due to Transport of Anthropogenic Marine Debris By Ocean Circulation	Nikolai Maximenko	University of Hawaii	USA
	Nikolai Maximenko[1], Jan Hafner[1], Masafumi Kamachi[2], Amy MacFadyen[3], Cathryn Clarke Murray[4], James Carlton[5], Gregory Ruiz[6] | [1]University of Hawaii, United States, [2]JAMSTEC, Japan, [3]NOAA Office of Response and Restoration, Emergency Response Division, United States, [4]Institute of Ocean Sciences, Canada, [5]Williams College, United States, [6]Smithsonian Institution, United States			
227	Coastal and Regional Sea Level Rise in Indonesia	Julia Illigner	GFZ	DE
	Julia Illigner[1] | [1]GFZ-German Research Centre for Geosciences, Potsdam, Germany			

228	Recent Developments in Altimeter Data Assimilation in the Global FOAM System	Daniel Lea	Met Office	UK
	Daniel Lea[1], Matthew Martin[1], Daley Calvert[1], Jennie Waters[1] | [1]Met Office, Exeter, United Kingdom			
229	Influence of Eddies and Tropical Cyclone Heat Potential on Intensification Changes of Tropical Cyclones in the North Indian Ocean	Debadatta Swain	Indian Institute of Technology Bhubaneswar	IN
	Babita Jangir[1], Samar Ghose[1], Debadatta Swain[1] | [1]Indian Institute of Technology Bhubaneswar, Argul, India			
230	Altimetry and Ocean Prediction: A GODAE OceanView Perspective	Eric Chassignet	COAPS-Florida State University	USA
	Eric Chassignet[1], GODAE OceanView Science Team[2] | [1]COAPS-Florida State University, Tallahassee, United States, 2GODAE OceanView			
231	Comparison of Sea Level Time Series from Coastal Altimetry and In-Situ Observations in the Mexican Pacific Coast	Jorge Manuel Montes Arechiga	Universidad De Guadalajara	MX
	Jorge Manuel Montes Arechiga[1], Anatoliy E. Filonov[1], Diego A. Pantoja González[1], Iryna Tereshchenko[1] | [1]Universidad De Guadalajara, Guadalajara, Mexico			
232	Assessment of Ocean Models Against Altimetric and Gravimetric Measurements from Space	Luciana Fenoglio	University of Bonn	DE
	Luciana Fenoglio[1], Joanna Staneva[2], Andrea Storto[3], Antonio Bonaduce[4], Bernd Uebbing[1], Roelof Rietbroek[1], Jürgen Kusche[1] | [1]Institute of Geodesy, University of Bonn, Bonn, Germany, [2]Institute of Coastal Research Helmholtz-Zentrum, Geesthacht, Germany, [3]NATO Centre for Maritime Research, La Spezia, Italy, [4]Mercator Ocean, Ramonville St-Agne, France			
11.	**Outreach, Education and Altimetric Data Services**			
233	SAR Altimetry Processing on Demand Service for CryoSat-2 and Sentinel-3 at ESA G-POD	Jérôme Benveniste	ESA	IT
	Jérôme Benveniste[1], Salvatore Dinardo[2], Giovanni Sabatino[3], Marco Restano[4], Américo Ambrózio[5] | [1]ESA-ESRIN, Frascati, Italy, [2]He Space-EUMETSAT, Darmstad, Germany, [3]Progressive Systems-ESRIN, Frascati, Italy,[4]SERCO/ESA-ESRIN, Frascati, Italy, [5]DEIMOS/ESA-ESRIN, Frascati, Italy			
234	Broadview Radar Altimetry Toolbox	Albert Garcia-Mondejar	Isardsat	ES
	Albert Garcia-Mondejar[1], Roger Escolà[1], Gorka Moyano[1], Mònica Roca[1], Miguel Terra- Homem[2], Ana Friaças[2], Fernando Martinho[2], Ernst Schrama[3], Marc Naeije[3], Marco Restano[4], Americo Ambrozio[5], Jérôme Benveniste[6] | [1]Isardsat Ltd., Guildford, United Kingdom, [2]DEIMOS Engenharia, Lisbon, Portugal, [3]TU Delft, Faculty of Aerospace Engineering, Delft, The Netherlands, [4]SERCO/ESA-ESRIN, Frascati, Italy, [5]DEIMOS/ESA-ESRIN, Frascati, Italy [6]ESA-ESRIN, Frascati, Italy			

235	GOCE User Toolbox and Tutorial	Per Knudsen	DTU Space	DK
	Per Knudsen[1], Jerome Benveniste[2], Et All[3] | [1]DTU Space, Kongens Lyngby, Denmark, [2]ESA-ESRIN, Frascati, Italy, [3]GUT Team			
236	Four Years of G-POD SAR Service: A Story of Success	Salvatore Dinardo	ESA	IT
	Salvatore Dinardo[5], Jerome Benveniste[1], Giovanni Sabatino[2], Marco Restano[3], Americo Ambrozio[4] | [1]ESA-ESRIN, Frascati, Italy, [2]ESA-RSS, Frascati, Italy, [3]Serco-ESRIN, Frascati, Italy, [4]DEIMOS-ESRIN, Frascati, Italy, [5]He Space, Darmstadt, Germany			
237	25 Years of Societal Benefits from Ocean Altimetry Mission Data	Margaret Srinivasan	JPL	USA
	Margaret Srinivasan[1] | [1]Jet Propulsion Laboratory, Pasadena, United States			
238	The Research and User Support (RUS) Service: a New Free Expert Service for Sentinel Data Users	Isabelle Soleilhavoup	NOVELTIS	FR
	Isabelle Soleilhavoup[1], Eric Jeansou[1], Pierre Fabry[3], Eric Guzzonato[2], Brice Mora[2], Sylvie Remondiere[4], Francesco Palazzo[4] | [1]NOVELTIS, Labege, France, [2]C-S, Toulouse, France, [3]Along-Track, Brest, France, [4]Serco, Roma, Italia			
239	Outreaching Hydrology from Space & SWO	Vinca Rosmorduc	CLS	FR
	Vinca Rosmorduc[1], Nicolas Picot[2] | [1]CLS, Ramonville Stagne, France, [2]CNES, Toulouse, France			

12. Outlook on Future Missions Requirements

240	Contribution of Wide-Swath Altimetry Missions to the Ocean Analysis and Forecasting System in the Iberia-Biscay-Ireland (IBI) Region	Mounir Benkiran	Mercator-océan	FR
	Mounir Benkiran[1], Antonio Bonaduce[1], Elisabeth Rémy[1], Pierre-Yves Le traon[1,2] | [1]Mercator-océan, Ramonville St-agne, France, [2]IFREMER, Toulouse, France			
241	Improved Retrieval of Titan Surface Topography from the Delay-Doppler Algorithm Applied to Cassini Radar Altimeter Data	Valerio Poggiali	Cornell University	USA
	Valerio Poggiali[1], Alexander G. Hayes[1], Marco Mastrogiuseppe[2], Roberto Seu[2], Joseph Mullen[1], Peter G. Ford[3], Samuel Birch[1], Mariacarmela Raguso[2] | [1]Cornell University, Ithaca, United States, [2]La Sapienza Universita di Roma, Roma, Italy, [3]MIT, Cambridge, United States			
242	New Altimetry Missions to Observe the Cryosphere	Bjoern Barthen	Airbus	DE
	Bjoern Barthen[1], Robert Cullen[2], Yves Le Roy[3], Harald Feuer[1], Klaus-Werner Kruse[1], Friedhelm Rostan[1] | [1]Airbus, Immenstaad, Germany, [2]ESQ, Noordwijk, The Netherlands, [3]Thales Alenia Space, Toulouse, France			

243	Data-Driven and Learning-Based Approaches for the Spatio-Temporal Interpolation of SLA Fields from Current and Future Satellite-Derived Altimeter Data	Ronan Fablet	Imt Atlantique	FR
	Ronan Fablet[1], Manuel Lopez-Radcenco[1], Said Ouala[1], Redouane Lguensat[1,2], Laura Gomez-Navarro[2,3], Ananda Pascual[3], Fabrice Collard[5], Lucile Gaultier[5], Bertrand Chapron[4], Jacques Verron[2] | [1]Imt Atlantique, Brest, France, [2]IGE, CNRS, Grenoble, France, [3]IMEDEA, Esporles, Spain, [4]Ifremer, LOPS, Brest, France, [5]ODL, Brest, France			
244	Experiment at the International Space Station: a Microwave Radar With Scanning Fan Beam Antenna at Nadir Probing	Vladimir Karaev	Institute of Applied Physics Ras	RU
	Vladimir Karaev[1], Dr. Maria Panfilova[1], Dr. Yury Titchenko[1], Eugeny Meshkov[1], Maria Ryabkova[1] | [1]Institute of Applied Physics Ras, Nizhny Novgorod, Russian Federation			
245	On the Assimilation of High-Resolution Wide-Swath Altimetric Data	Emmanuel Cosme	University of Grenoble Alpes, IRD, CNRS, Grenoble INP, IGE	FR
	Emmanuel Cosme[1], Nora Poel[1], Laura Gómez Navarro[1,2], Jean-Michel Brankart[1], Julien Le Sommer[1], Ananda Pascual[2], Jean-Marc Molines[1] | [1]University of Grenoble Alpes, IRD, CNRS, Grenoble INP, IGE, Grenoble, France, [2]IMEDEA (UIB-CSIC), Esporles, Spain			
246	Ku/Ka Radar Altimeter for a Polar Ice and Snow Topography Mission	Yves Le Roy	Thales Alenia Space	FR
	Yves Le Roy[1], Benjamin Carayon[1], Robert Cullen[2], Erik De Witte[2] | [1]Thales Alenia Space, Toulouse, France, [2]ESA-ESTEC, Noordwijk, The The Netherlands			
247	Sentinel-3 Topography Mission Payload	Alexandre Houpert	Thales Alenia Space	FR
	Alexandre Houpert[1], Franck Borde[2], Constantin Mavrocordatos[2], Vanin Felice[2] | [1]Thales Alenia Space, Toulouse, France, [2]ESA-ESTEC, Noordwijk, The The Netherlands			
248	Swath Altimetry for Operational Oceanography	Franck Demeestere	Thales Alenia Space	FR
	Franck Demeestere[1], Anne Duclos[1], Laurent Phalippou, Laurent Rey[1], Benjamin Monteillet[1], Erik De Witte[2], Craig Donlon[2], Cécile Cheymol[3], Alain Mallet[3] | [1]Thales Alenia Space, Toulouse, France, [2]ESA-ESTEC, Noordwijk, The Netherlands, [3]CNES, Toulouse, France			
249	Design Status of the Ka-Band Scanning Doppler Scatterometer for the SKIM Mission	Eric Caubet	Thales Alenia Space	FR
	Eric Caubet[1], Erik De Witte[2], Bertrand Chapron[4], Laurent Phalippou[1], Céline Tison[3], Frédéric Nouguier[4], Jean-Claude Lalaurie[3], Laurent Rey[1] | [1]Thales Alenia Space, Toulouse, France, [2]ESA-ESTEC, Noordwijk, The Netherlands, [3]CNES, Toulouse, France, [4]IFREMER, Plouzané, France			
250	Technical Challenges and Status of the Ka-Band Interferometric Radio-Frequence Unit for the SWOT Mission	Frederic Robert	Thales Alenia Space	FR
	Sophie Ramongassie[1], Frederic Robert[1], Nicolas Taveneau[1], Guy Michaud[1], Cecile Cheymol[2], Emmanuel Robert[2], Pierre Sengenes[2] | [1]Thales Alenia Space, Toulouse, France, [2]CNES, Toulouse, France			

251	Sentinel-6 Level-1 Poseidon-4 Ground Processor Prototype Architecture and Processing Modes	Gorka Moyano	IsardSAT	ES
	Gorka Moyano[1], Eduard Makhoul[1], Roger Escolà[1], Pablo García[1], Albert Garcia-Mondéjar[1], Mònica Roca[1], Marco Fornari[2], Robert Cullen[3] | [1]IsardSAT, Barcelona, Spain, [2]RHEA-ESTEC, Noordwijk, The Netherlands, [3]ESA-ESTEC, Noordwijk, The Netherlands			
252	Surface Water Ocean Topography Mission Retrievals in the Ice-Covered Polar Oceans	Thomas Armitage	JPL	US
	Thomas Armitage[1], Ron Kwok[1] | [1]JPL, Pasadena, United States			
253	High Temporal SSH Measurements Using Wideband Ku-Band Signals of Opportunity	Rashmi Shah	NASA	USA
	Rashmi Shah[1], James Garrison[2], Soon Chye Ho[2], Zhijin Li[1], Y. Tony Song[1] | [1]JPL-NASA, Pasadena, United States, [2]Purdue University, West Lafayette, United States			
254	SWOT in the Tropics: Designing a Joint In Situ Experiment with SWOT during the Fast-Sampling Phase to Sample Small-Scale Dynamics around New-Caledonia	Guillaume Sérazin	LEGOS/IRD	FR
	Guillaume Sérazin[1], Frédéric Marin[1], Lionel Gourdeau[1], Mei-Ling Dabat[2] | [1]LEGOS/IRD, Toulouse, France, [2]LEGOS, Toulouse, France			
255	Transition of SAR Interferometric Altimetry from R&D to Operations	Mark Drinkwater	ESA	NL
	Mark Drinkwater[1], Robert Cullen[1], Craig Donlon[1], Noel Gourmelen[1], Michael Kern[1], Constantin Mavrocordatos[1], Gerhard Ressler[1], Andrew Shepherd[2], Noel Gourmelen[3] | [1]ESA, Noordwijk, The Netherlands, [2]University of Leeds, Leeds, United Kingdom, [3]University of Edinburgh, Edinburgh, United Kingdom			
256	S6 P4 GPP: The Sentinel-6 Poseidon-4 Ground Processor Prototype. Performance Validation	Eduard Makhoul	Isardsat	ES
	Eduard Makhoul[1], Gorka Moyano[1], Roger Escolà[1], Pablo García[1], Albert Garcia-Mondéjar[2], Mònica Roca[1], Marco Fornari[3], Mieke Kuschnerus[4], Robert Cullen[4] | [1]Isardsat, Barcelona, Spain, [2]IsardSAT Ltd., Guildford, United Kingdom, [3]ESA-RHEA, Noordwijk, The Netherlands, [4]ESA-ESTEC, Noordwijk, The Netherlands			
257	The Altimeter Product Suite for Sentinel-6/Jason-CS Mission	Remko Scharroo	EUMETSAT	DE
	Remko Scharroo[1], Cristina Martin-Puig[1], Carolina Nogueira Loddo[1], Rob Cullen[2], Marco Fornari[2], Mònica Roca[3], Thomas Moreau[4] | [1]EUMETSAT, Darmstadt, Germany, [2]ESA-ESTEC, Noordwijk, The Netherlands, [3]IsardSAT, Barcelona, France, [4]CLS, Ramonville-St. Agne, France			

4 Abstracts

SYMPOSIUM PLENARY SESSION: Opening, Keynote Presentations

KEYNOTE: Early Development of Satellite Altimetry

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The satellite altimeter measurement, as implemented by the TOPEX/Poseidon and JASON mission series, is one of the more important space satellite-based measurements for studying the interactions of the Earth's dynamical systems. The 26-year record of global sea level rise and its regional variations provide important indicators of climate change. The climate quality accuracy of these measurements is made possible by the combination of very accurate radiometric measurement of sea surface height measurements and very accurate determination of the satellite orbit. The necessity that the accurate measurement of height be made from a platform that is positioned relative to the Earth's mass center with demanding accuracy places the realization of the measurement firmly within the field of satellite geodesy. The accuracy of the terrestrial reference frame, the gravity model and the surface-based tracking systems all play central roles in meeting the requirements for observing change in global sea level and the general ocean circulation. While remarkable progress has been made in these three pillars during the past three decades, at the initiation of the TOPEX/Poseidon Mission, the orbit accuracy was three orders of magnitude less than required and was the fundamental limitation on mission success. The primary error source in providing the required orbit accuracy resided in errors in the longwave components of the earth's gravity field. The tracking station accuracy and distribution were also contributing factors. This presentation will discuss the Precision Orbit Determination capabilities as related to the accuracy required to satisfy theTOPEX/Poseidon mission requirements, at the time the mission was selected, the efforts expended to achieve the three-order magnitude improvement required to deliver acceptable science data records at mission initiation and the relevant progress in this area during the subsequent decades.

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KEYNOTE: Legacy Achievements of the First 25 Years of the TOPEX/Poseidon and Jason Series

Leuliette E.[1]*, Bonnefond P.*[2]*, Scharroo R.*[3]*, Willis J.*[4]

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The launch of the NASA/CNES TOPEX/Poseidon mission 25 years ago ushered in a new era of oceanography by greatly exceeding its goal to make highly accurate, global measurements of sea levels. In this presentation, we review the legacy of TOPEX/Poseidon and its successor Jason missions, including:

• Building the global mean sea level climate record

• A greatly improved mapping of the global tides

• The first global views of seasonal changes of currents.

• A census of mesoscale eddies and their trajectories as well as identifying new phenomena such as stationary mesoscale jet-like features in the ocean

• Monitoring large-scale ocean features like Rossby and Kelvin waves and studied such long-scale phenomena as El Niño, La Niña, and the Pacific Decadal Oscillation

• Improved our knowledge of Earth's gravity field, bathymetry, and mean dynamic topography.

• The of monitoring lake and river levels with altimetry

• Providing global data to validate models of ocean circulation, and

• The demonstration of operational monitoring of sea state and mapping of changes in heat stored in the upper ocean for tropical cyclone intensity forecasts for meteorological agencies.

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KEYNOTE: Assessment of the Global Mean Sea Level Budget over the Altimetry Era: an International Initiative

Cazenave A.[1,2]*, Meyssignac B.*[1]*, The WCRP Global Sea Level Budget Group.*[1]

[1]*LEGOS, TOULOUSE CEDEX 9, France, 2ISSI, Bern, Switzerland*

Accurate assessment of present-day global mean sea level variations and its components (ocean thermal expansion, ice sheet mass loss, glaciers mass change, changes in land water storage, atmospheric water vapour content, etc.) is important for many reasons. The global mean sea level is an integrator of changes occurring in the climate system in response to unforced climate variability as well as natural and anthropogenic forcing factors. Temporal evolution of the global mean sea level allows detecting changes (e.g., acceleration) occuring in one or several components. Study of the sea level budget provides constraints on missing contributions such as the unsurveyed deep ocean and Arctic region. It also allows constraining poorly known contributions, e.g., the land water component. In the context of the Grand Challenge entitled “Regional Sea

Level and Coastal Impacts" of the World Climate Research Programme, an international effort involving the sea level community worldwide has been recently initiated with the objective of assessing the various data sets used to estimate components of the sea level budget during the altimetry era (1993 to present). These data sets are based on the combination of a broad range of space-based and in situ observations, and model estimates. Evaluating their quality, quantifying uncertainties and identifying sources of discrepancies between component estimates, including the altimetry-based sea level time series, are extremely useful for various applications in climate research. The current effort involves several tens of scientists from about sixty research teams worldwide (www.wcrp-climate.org/grand-challenges/gc-sea-level). Here we review the status of the ongoing assessment. We also discuss lessons learned from this global assessment, focusing on science findings and remaining key uncertainties.

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KEYNOTE: A 25-Year Record of Global Mean Sea Level Change: What Have We Learned?

Nerem R.[1], Cazenave A.[2]

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The 25-year record of global sea level change from satellite altimetry is one of our most valuable climate data records of how the Earth is responding to anthropogenic warming. But what have we learned from this record? This presentation will summarize our current understanding of sea level change based on the satellite altimeter record. One important fact we have learned from these observations is that the 25-year altimeter record occurs during a remarkably unusual time in the 100+ year sea level record. As a result, we must ask ourselves how this affects our interpretation of the altimeter record – are the changes we are observing short term or long term? Sorting out the natural and anthropogenic climate signals is a continuing challenge as we move into the future and look for answers to the many questions that remain. We know now that this record was impacted by the eruption of Mount Pinatubo about a year prior to the launch of TOPEX/Poseidon. Most of the interannual variations in the record are related to ENSO, but no two events look the same. The rate of sea level rise, ~3 mm/year over 25 years, represents an acceleration relative to the tide gauge record of sea level change. Now, it appears that an acceleration can be detected in the altimeter record itself, and this acceleration appears to be driven by ice melting in Greenland and Antarctica. This is also an appropriate time to pause and ask if we have the measurements we need to answer these questions, or if new measurements are needed? Several new satellite measurement systems are planned – how will they enhance our understanding of sea level change? This presentation will look back at the 25-year satellite altimeter record – but also look forward to measurements and discoveries yet to be made.

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KEYNOTE: Global Ocean Circulation from Satellite Altimetry: Progress and Future Challenges

Fu L.[1]

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The concept of measuring the shape of the sea surface from an orbiting satellite for determining the geoid and the ocean surface topography was formed in the late 1960s. The first demonstration of satellite altimetry was carried out by the missions of Skylab and Geos-3 of the early-mid 1970s. Launched in 1978, Seasat revealed the variability of the global ocean surface topography for the first time. The findings of the short-lived Seasat confirmed the global presence of the mesoscale ocean eddies that had been discovered in the 1970s from in-situ observations as the most energetic element of ocean circulation. Recognizing the potential breakthrough in oceanography from satellite altimetry, NASA and CNES began a long-lasting partnership in altimetry missions following Seasat, leading to TOPEX/Poseidon (TP), which had eventually revolutionized our knowledge of the global ocean circulation.

While T/P was being developed, the US Navy launched Geosat, which was essentially a Seasat follow-on in an ocean-mesoscale-resolving orbit. A great deal was learned from Geosat on mesoscale dynamics and the performance of satellite altimetry. The major impact of T/P, lasting from 1992-2005, was delivered from its mission design, which was optimized for determining the full spectrum of ocean variability with much improved suite of sensors for altimetry and precision orbit determination, leading to the first global determination of ocean basin-scale variability, including planetary-scale waves on a wide range of time scales associated with the response to rapid atmospheric forcing as well as seasonal and interannual climate variations such as El Nino Southern Oscillation. T/P has also made revolutionary advances in the knowledge of ocean tides.

The synergy of T/P with the ERS-1 and -2 missions led to a global dataset providing the first routine information of the global ocean circulation. This data stream was the core of the World Ocean Circulation Experiment, which deployed global arrays of ocean measurements in concert with satellite observations in the 1990s, leading to the transformation of oceanography into a global enterprise with modeling and data assimilation, paving the way of global operational oceanography. This achievement has been continued by the launch of a series of missions with the capability of T/P: the Jason series, plus other multi-purpose missions like Envisat, and exploratory missions like Altika, Cryosat, culminating with the operational missions like Sentinel and Jason-CS. This ever-increasing record has revealed the impact of long-term climate change on global and regional sea levels.

The pursuit of geoid determination has been fulfilled by GRACE and GOCE in the decade of the 2000s, leading to the determination of the absolute ocean circulation down to scales less than 100 km. The future challenge lies in the measurement of the small-scale ocean processes that control the dispersion of ocean properties and the dissipation of ocean circulation energy as well as coastal processes. Missions using new technologies like SWOT are being implemented to address the challenge in the next decade.

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KEYNOTE: Satellite Altimetry and the Copernicus Marine Service: Status and Perspectives

Le Traon P.[1]

[1]*Mercator Ocean, Ramonville st Agne, France*

The Copernicus Marine Environment Monitoring Service (CMEMS) is one of the six pillar services of the European Copernicus programme. The CMEMS provides regular and systematic reference information on the physical state, variability and dynamics of the ocean, ice and marine ecosystems for the global ocean and the European regional seas. CMEMS provides a sustainable response to European user needs in four areas of benefits: (i) maritime safety, (ii) marine resources, (iii) coastal and marine environment, and (iv) weather, seasonal forecast and climate. A major objective of the CMEMS is to deliver and maintain a state-of-the-art European service responding to public and private intermediate user needs, and thus involving explicitly and transparently these users in the service delivery definition.

An overview of the Copernicus Marine Service, its organisation, users/applications and initial achievements will be given. We will then focus on the unique role of altimetry and illustrate the high dependency of CMEMS systems with respect to the altimeter constellation. Improvements of altimetry thanks to SAR processing and its impact for ocean analysis and forecasting will also be discussed. Perspectives for the evolution of CMEMS for the next decade will be finally given. This will include a discussion on CMEMS long term requirements for satellite altimetry and an analysis of the role and impact of wide swath altimetry for operational oceanography.

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KEYNOTE: Progresses of Altimetry for Marine Ecology: from a Dataset for Biophysical Studies, to a Tool for Conservation Policies

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Altimetry has revolutionised our view of the physical ocean by unveiling large part of the mesoscale circulation. However, the weeks-to-months timescale over which mesoscale eddies evolve, also encompasses key ecological processes of marine life, like notably phytoplanktonic doubling time, bloom cycles, and even the duration of foraging trip of marine top predators. Due to this biophysical resonance, altimetry observations have been used as a powerful dataset for studying the structuring effect of the ocean circulation over the marine ecosystems. Examples include redistribution of nutrients and stirring patterns which organise planktonic patterns, plankton diversity induced by lateral mixing, and detection of frontal features where biomass transfer across the trophic chain is enhanced. Altimetry has played as well a central role in situ biogeochemical experiments, like notably iron fertilisation studies, by allowing ships to track in near-real time biogeochemically active water masses and their dynamical boundaries for several weeks. More recently, integration of altimetry analysis with biological data (e.g., animal telemetry) is playing an important role in supporting conservation efforts, like in zoning the open ocean for establishing marine protected areas. This talk will review the role of altimetry in marine ecology, from its initial qualitative comparison to ocean colour images, to more recent "end-to-end" ecological studies, discussing the potential of future missions like SWOT in biogeochemical and ecological applications.

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KEYNOTE: The Ocean Mean Dynamic Topography: 25 Years of Improvements

Rio M.[1]*, Mulet S.*[1]*, Dibarboure G.*[2]*, Picot N.*[2]

[1]*CLS, Ramonville Saint Agne, France,* [2]*CNES, Toulouse, France*

Since the very beginning of altimetry, 25 years ago, the lack of an accurate geoid has hampered the direct use of altimeter signal for computing the ocean absolute dynamic topography and, hence, by geostrophy, the ocean surface currents. To cope with the uncertainty on the geoid, the so-called ‘repeat-track’ method has been developed and Sea Level Anomalies (SLA) are computed with centimetre accuracy. To correctly analyse the altimeter signal and assimilate it into operational forecasting systems, the full dynamical signal needs to be reconstructed from the SLA. Knowledge of the ocean Mean Dynamic Topography (MDT) is therefore required with both high accuracy and high resolution.

At large spatial scale, the MDT may be obtained by filtering the difference between an altimetric Mean Sea Surface and a geoid model. The filtering length is imposed by the geoid commission and omission error level. With the launch of dedicated space gravity missions as CHAMP (2000), GRACE (2004) and GOCE (2009) huge improvements have been made in the last 20 years for the estimation of the geoid. Recent satellite-only geoid models based on GRACE and GOCE data have centimetre accuracy at spatial scales down to around 100 km.

To compute higher resolution MDT, a number of methodologies have been developed. The geoid itself can be improved at short scales locally using in-situ gravimetric data or globally using the shortest scales information of the altimetric Mean Sea Surface. On the other hand, the large-scale MDT based on the satellite-only geoid models may be improved thanks to the use of in-situ oceanographic measurements (drifting buoy velocities, dynamic heights from hydrological profiles). Alternatively, the synthesis of all available information (in-situ oceanographic data, altimetry) can be done in a dynamically consistent way through inverse modeling or through data assimilation into ocean general circulation models, whose outputs are then averaged to obtain an estimate of the ocean Mean Dynamic Topography.

The aim of this talk is to give an overview of the huge improvements that have been achieved in the past 25 years for the estimation of the ocean Mean Dynamic Topography thanks to the launch of dedicated space gravimetry missions, the development of new computation methodologies, and the increasing number of oceanographic in-situ data. Perspectives will also be given in the upcoming context of high resolution wide-swath altimetry, and increasing need for high resolution coastal products.

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KEYNOTE: Twenty-Five Years of Progress in Sea Floor Mapping by Satellite Altimetry

Smith W.[1], Sandwell D.[2], Marks K.[1], Andersen O.[3]

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Although ships equipped with deep-water multi-beam echo-sounding (MBES) swath mapping systems and satellite (GPS) navigation have been around for the last 25 years, they rarely collect data in unexplored ocean areas. The most accurate and detailed sea floor sounding data are mostly confined to shallow coastal areas around developed countries, and a few deep-water areas that have been the focus of particular efforts (such as the search for the missing Malasia Airlines flight MH370 aircraft). Almost all the global ocean floor area lies more than a few hundred kilometers from the nearest GPS-navigated MBES data, and global ocean floor depth models must rely on older, low-tech single-wide-beam echo soundings recorded on analog scrolls and often positioned with only celestial navigation (most of the available data in the remote oceans was collected prior to 1965). If the ocean floor area is divided into squares one nautical mile (1.85 km) on a side, and all data, both GPS-MBES and old, low-tech data, are combined, only 8 percent of squares have any data at all. For this reason, global ocean floor mapping relies on satellite altimetry to guide the interpolation of gaps in unmapped areas.

The largest variations in sea surface topography are time-invariant and exhibit geoid height anomalies produced by the Earth's gravity field. At high wavenumber (full wavelengths approximately 10 to 160 km) these anomalies are usually correlated with sea floor topography, but can also arise from sub-seafloor tectonic structure buried beneath seafloor sediment. Resolving anomalies at this scale requires satellite altimeter profiles of sea surface height along a dense network of ground tracks, so that the inter-track spacing adequately samples scales as short as 5 km or less.

The first altimeter mission to yield a dense network of tracks was the European Space Agency's ERS-1 mission, completed in March of 1995. Marine gravity maps made from these data were exhibited at the Spring 1995 Americal Geophysical Union meeting, and this may have prompted the U.S. Navy to release the Geosat dense track data, collected in 1985-86 but classified Secret until July 1995. Some southern ocean Geosat data had been previously released in 1990 and 1992, allowing algorithm development for bathymetric estimation from dense track altimetry.

After the 1990s there was a long period with no new dense-track altimetry, and so seafloor mapping made incremental improvements as geodesists learned to improve the along-track resolution at high wavenumber using specialized retrackers and high-data-rate filters designed to extract the seafloor topography signal.

With CryoSat-2 in a long-repeat orbit since 2010, and the Jason-1, Jason-2, and SARAL/AltiKa missions also going into dense-track orbits at the end of their primary missions, there is now a rennaissance in seafloor mapping. Efforts are underway to see how many previously uncharted seamounts may be found, and how much resolution may be squeezed out of the newer mission data.

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KEYNOTE: Assimilating Altimeter Observations in a High-Resolution Shelf-Seas Model – The Met Office 1.5km European North-West Shelf Forecasting System

King R.[1], Martin M.[1], While J.[1]

[1]UK Met Office, Exeter, United Kingdom

The Forecasting Ocean Assimilation Model (FOAM) is the short-range operational ocean prediction system at the UK Met Office consisting of global, basin-scale and shelf-seas systems. In 2017, we introduced the assimilation of satellite altimeter observations along with SST and in situ T/S observations into our operational 7km resolution shelf-seas forecasting system. This uses altimetry products which retain the tidal and atmospheric signals to match the physical processes in our ocean model.

We are now upgrading our system to use a new 1.5km resolution configuration covering the European North-

West Shelf which is capable of resolving mesoscale eddies, frontal jets, and internal tides. Our initial implementation, which is due to become operational in late-2018, will assimilate the same altimetry products as the existing 7km resolution system. In the low resolution system, the assimilation of altimeter observations helps to improve the 3D temperature and salinity structure as well as adding realistic eddying features. Here I will demonstrate the impact of these observations in our new high resolution system and compare to the existing low resolution system. I will also describe some of the remaining issues and look ahead to the assimilation developments planned to make better use of altimetry observations in our 1.5km resolution system.

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KEYNOTE: CryoSat-2 for Inland Water Applications – Potential, Challenges and Future Prospects

Kittel C.[1], Jiang L.[1,] Schneider R.[1,3], Andersen O.[2], Nielsen K.[2], Bauer-Gottwein P.[1]

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Hydrologists are increasingly exploiting advances in remote sensing technologies. Numerous studies have used altimetry observations from the ESA mission CryoSat-2 to extract water surface elevations (WSE) for inland water bodies such as lakes and rivers despite the satellite being primarily designed for cryospheric studies. Until the launch of Sentinel-3, CryoSat-2 was the only radar altimetry mission to operate in the high resolution Synthetic Aperture Radar (SAR) mode, and it is still the only mission operating in Synthetic Aperture Interferometric mode (SARIn) over selected inland regions like the Amazon (SAR mode), the Brahmaputra, the Tibetan Plateau and parts of the Zambezi (SARIn mode). The long-repeat orbit sampling pattern of CryoSat-2 is particularly interesting but challenges traditional processing methods for radar altimetry over inland water bodies and the way the observations are integrated in hydrological and hydrodynamic models.

In this study, we review the contribution of CryoSat-2 to hydrological applications. CryoSat-2's 369-repeat and the resulting drifting ground track pattern yield a higher overpass frequency over large water bodies compared to short-repeat missions. Moreover, a higher number of smaller water bodies are visited, at least sporadically. The unique sampling pattern has challenged the conventional "virtual station" approach used in river monitoring applications, where time series of WSE observations are extracted at specific locations along a river line. Instead, a longitudinal profile of the WSE in the river is obtained, offering new possibilities for hydraulic characterization of the river. Although the sampling pattern complicates temporal analysis, it has forced the development of new approaches in data analysis and assimilation and studies have shown the benefit of including CryoSat-2 observations, particularly by improving the hydraulic characterization even in highly monitored regions.

For short-repeat missions, simplified rectangular masks or thresholds can be used to extract observations over water bodies. However, to obtain all CryoSat-2 observations, a continuous river mask is required. Such masks can be obtained from optical imagery (e.g. Landsat or Sentinel-2) or from SAR imagery (e.g. Sentinel-1). Particularly the latter offers an interesting synergy with CryoSat-2 observations, as observations are available even for overcast conditions and at relatively high temporal resolution (12 days). Multi-temporal, high-resolution water masks are expected to increase the amount and quality of observations. Furthermore, the combination of dynamic water extent with WSE at high spatial resolution offers new opportunities to assess terrestrial water bodies. In this presentation, we will focus on the various ways, CryoSat-2 has challenged traditional radar altimetry data processing approaches whilst paving the way for SAR altimetry for inland water monitoring and topographical missions such as SWOT.

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KEYNOTE: Polar Altimetry

Shepherd A.[1], Wingham D.[2], Muir A.[2], Ridout A.[2], Gilbert L.[2], McMillan M.[1], Tilling R.[1], Konrad H.[1], Slater T.[1], Otosaka I.[1], Hogg A.[1], Gourmelen N.[3]

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Satellite and airborne altimetry have transformed our capacity to study the polar regions, and the past 25 years of altimeter measurements have painted a new and unique picture of how Earth's ice sheets, ice shelves, sea ice, and polar oceans evolve. As global temperatures have risen, so too have rates of snowfall, ice melting, and sea level rise, and each of these changes impacts upon the neighbouring land, marine, and atmospheric environments. Altimeter measurements are now central to our awareness and understanding of Arctic and Antarctic environmental change. A case in point is the marine ice sheet instability that is underway in West Antarctica, widely understood to be among the greatest contemporary imbalances in the climate system, whose evolution has been charted in altimeter data since its onset.

This paper introduces a series of recent studies that have allowed both long-standing and unanticipated scientific problems in cryospheric research to be solved over the past five years. It also reports on the landmark studies in altimeter retrievals that underpin these discoveries. We discuss the techniques that have been developed to allow multi-decadal measurements of land ice, sea ice, and polar ocean elevation change, paying attention to new waveform re-tracking, interferometric processing, geophysical corrections, and approaches to time-series formation. This includes work on waveform deconvolution, and dual-frequency radar altimetry. We also present case studies on the use of these data to record multi-decadal trends in ice sheet mass balance, sea ice volume, and ocean circulation. Finally, we focus on a collection of very recent discoveries, including developing and utilising full swath-interferometric processing for mapping ice sheet elevation and elevation change, exploiting Altika and Sentinel-3 for land and sea ice studies in both hemispheres, tracking grounding line migration, verification of global sea level projections, partitioning snow and ice mass trends, and detecting the fingerprint of the seasonal melting cycle. In all cases, we explain how satellite and airborne altimetry have informed thinking across the wider scientific community.

1. Shepherd A, et al., (2012) A reconciled estimate of ice-sheet mass balance, Science, 338

2. Leeson A., et al., (2015) Supraglacial lakes on the Greenland ice sheet advance inland under warming climate, Nature Climate Change, 5

3. Tilling R., et al., (2015) Increased Arctic sea ice volume after anomalously low melting in 2013, Nature Geoscience, 8

4. Shepherd, A., and Nowicki, S., (2017) Improvements in ice-sheet sea-level projections, Nature Climate Change, 7

5. Konrad, H., et al., (2018) Net retreat of Antarctic glacier grounding lines, Nature Geoscience, 11

6. Shepherd, A., et al., (In review) Antarctica from Space, Nature.

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KEYNOTE: The Younger, Thinner, Faster Arctic Sea Ice Cover: Tracking Change over Fifteen Years

Farrell S.[1,2], Hutchings J.[3], Duncan K.[1,2], McCurry J.[1,2]

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Satellite laser and radar altimeters observing the polar and subpolar seas now provide extensive monitoring of the sea ice cover, spanning two decades. We use these novel data to derive sea ice freeboard, thickness, and surface roughness, tracking changes in the inter-annual variability of Arctic Ocean sea ice over a fifteen-year period, between 2003 and 2017. High-resolution measurements from airborne laser and radar altimeters, and visible cameras operated during IceBridge surveys of the winter ice pack, are used to gain further insights of the deformation characteristics of the Arctic ice cover. In anticipation of the launch of NASA's ICESat-2 mission in 2018, we describe our recent work towards creating a synthesized time series of Arctic sea ice thickness, using measurements collected by ICESat, CryoSat-2 and IceBridge. This includes an improved tracking of the trends and variability in the first-year and multi-year sea ice thickness distributions. Combining altimeter measurements with satellite scatterometer observations from Metop-A/-B, and synthetic aperture radar (SAR) composites from Sentinel-1 A and B, provides new insights into the dynamic changes occurring in the Arctic sea ice cover today. By improving knowledge of the complex relationship between the ice cover and the polar climate system, our goal is to provide multi-sensor data products that advance capabilities to model and predict future change. We disseminate data products publicly through the NOAA Laboratory for Satellite Altimetry data catalogue and NOAA PolarWatch web portal.

During the observation period significant declines have been observed in three key variables typically used to describe the sea ice cover: extent, age and thickness. September sea ice extent is now declining at a rate of 13.4% per decade, relative to the long-term average. The sea ice cover comprises ice of different ages, and the location and extent of older, thicker, multi-year ice influences both the strength and vulnerability of the overall ice pack during the summer melt season. In the last fifteen years the amount of multi-year ice covering the Arctic Ocean has decreased from ~40 % to ~20 %. Simultaneously, satellite altimeter observations from ICESat and CryoSat-2 indicate a substantial loss in sea thickness and volume during the first half of the record, followed more recently by increased inter-annual variability. Pan-Arctic ice drift and deformation rates have increased over the same time period. A diminishing ice cover preconditions the pack for further loss, modifying the mass and energy budgets of the Arctic Ocean. These changes alter planetary albedo, ocean-atmosphere heat fluxes, and the flux of freshwater from the Arctic Ocean, thus impacting thermohaline circulation and having wide-ranging climate, ecological, and socio-economic impacts.

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Open Ocean #1: Large-Scale Ocean Circulation and Sea-Level Session

KEYNOTE: Global Sea Level Budget Assessment: Preliminary Results From ESA's CCI Sea Level Budget Closure Project

Horwath M.[1], Cazenave A.[2], Palanisamy H.[2], Marzeion B.[3], Paul F.[4], Le Bris R.[4], Hogg A.[5], Otosaka I.[5], Shepherd A.[5], Döll P.[6], Caceres D.[6], Müller Schmied H.[6], Johannessen J.[7], Nilsen .J[7], Raj R.[7], Forsberg R.[8], Sandberg Sørensen L.[8], Barletta V.[8], Knudsen P.[8], Andersen O.[8], Villadsen H.[8], Merchant C.[9], Macintosh C.[9], Old C.[9], von Schuckmann K.[10], Gutknecht B.[1], Novotny K.[1], Groh A.[1], Benveniste J.[11]

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Studies of the sea level budget are a means of assessing and understanding how sea level is changing and what are the causes. Closure of the total sea level budget implies that the observed changes of global mean sea level as determined from satellite altimetry equal the sum of observed (or otherwise assessed) contributions, namely changes in ocean mass and ocean thermal expansion and haline contraction. Here, ocean mass changes can be either derived from GRACE satellite gravimetry (since 2002) or from assessments of the individual contributions from glaciers, ice sheets, land water storage, snow pack and atmospheric water content. Estimates of thermosteric sea level are obtained from ocean in situ measurements with additional plans for the inclusion of satellite derived Sea Surface Temperature information. Misclosure of the sea level budget indicates errors in some of the components or contributions from missing or unassessed elements in the budget.

ESA's Climate Change Initiative (CCI) has conducted a number of projects related to sea level. Among those projects, the Sea Level CCI project, the Greenland and Antarctic Ice Sheet CCI projects and the Glaciers CCI project directly benefit from satellite altimetry data. The Glaciers CCI project and the Sea Surface Temperature CCI project provide additional insights into phenomena related to sea level change.

The aim of the ongoing CCI Sea Level Budget Closure project is to use the CCI data products, together with further data products provided by the project partners to re-assess the sea level budget. Specifically, the project further develops and analyzes products based on the CCI projects mentioned above in conjunction with in situ data for ocean thermal expansion (e.g., Argo), GRACE-based ocean mass change assessments, and model-based data for glaciers and land hydrology. The work benefits from directly involving the expertise on the product generation for all the involved sea level contributions.

The presentation will report on preliminary assessments of global sea level budget closure. We focus on two periods: 1993-2015 (the altimetry period) and 2003-2015 (the GRACE / Argo period). We consider the budget of the long-term trends as well as the budget of the overlaid interannual variations. A special focus is on the account for uncertainties of the individual contributions, building on the expertise of all project partners.

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KEYNOTE: Causes of Sea-Level Variability: Oceanic Chaos Versus Atmospheric Forcing.

Penduff T.[1], Close S.[1], Leroux S.[2,1], Garcia-Gomez I.[1], Sérazin G.[3,1], Molines J.[1], Barnier B.[1], Bessières L.[4], Terray L.[4]

1IGE-MEOM, Grenoble, France, 2Ocean Next, Grenoble, France, 3LEGOS, Toulouse, France, 4CERFACS-CECI, Toulouse, France

Space altimetry has revolutionized physical oceanography by providing a continuous and global monitoring of the sea-surface height (SSH) for the last 25 years. The variability of this surface is accurately depicted over a wide range of scales, ranging from the size of mesocale structures (about 100km) to the scale of the Earth, with periods ranging from weeks to decades. Physical oceanographers are jointly using altimeter data, theoretical approaches and numerical simulations to show the key importance of the ubiquitous mesoscale turbulence. This relatively fast and small variability spontaneously emerges in the ocean and is involved in many larger-scale processes (transport of heat, freshwater and nutrients, dynamical balances of main currents, air-sea interactions, etc).

Mesoscale dynamics are strongly non-linear and have a chaotic evolution: the evolution of eddies is highly sensitive to slight changes in their initialization, which makes their operational forecasting challenging. Unlike the non-turbulent ocean models used in most current climate projections, the turbulent ocean models that will be used in future climate projections spontaneously generate a substantial intrinsic and chaotic variability reaching multi-decadal/basin scales, with a marked signature on SSH and SST where air--sea fluxes are maximum in Nature. Whether and how this ocean--driven low-frequency chaotic variability may ultimately impact the atmosphere and the climate is an important but unsettled question.

Before addressing this question in fully-coupled simulations, it is necessary to simulate, characterize and quantify over long periods the chaotic character and the scales of the low-frequency oceanic variability under a realistic forcing, with a focus on SSH and other climate-relevant indexes. In the framework of the OCCIPUT and PIRATE projects, we have performed and are currently analyzing a 50-member ensemble of 1/4° global ocean/sea--ice NEMO-based 1/4° hindcasts driven by the same reanalyzed 1960-2015 atmospheric forcing. After a common spinup, the spread of the ensemble is seeded by applying stochastic perturbations within each member for one year; eddy--eddy interactions then take control of the subsequent growth of the ensemble spread and of its cascade toward long space and time scales.

Along with reduced-size North Atlantic sensitivity experiments, this global ensemble simulation provides the first probabilistic description of the global ocean/sea-ice evolution over the last 5 decades over a wide range of spatio-temporal scales, direct estimates of the chaotic ocean variability (from the ensemble spread) and of the actual constraint exerted by the atmosphere (variability of the ensemble mean). We will present the strong imprints of the atmospherically-modulated ocean chaotic variability on SSH, and on other climate-relevant indices (heat content and transport, overturning circulation), with a focus on interannual and longer time scales. These analyses show that certain climate-relevant oceanic signals cannot be unambiguously attributed to the atmospheric variability. This raises new issues for the detection, attribution, and interpretation of the oceanic variability and trends in the presence of mesoscale turbulence.

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Has the Gulf Stream Slowed Down during 1993-2016?

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The Gulf Stream (GS), the western boundary current in the North Atlantic, plays an important role in the climate system through both dynamic and thermodynamic processes. More recent studies have linked the GS to the accelerated sea level rise along the U.S. east coast. Using the 24-year altimeter sea surface height (SSH) measurements, GS properties (position, speed, width, and transport) are derived and analyzed in the region from 80°W to 50°W. During the study period 1993-2016, the GS experiences a strong southward shift dominated by the region east of 65°W after the GS passes the New England Seamount. This southward shift is accompanied by a weakening of the GS, associated with the SSH increase to the north of the GS. However, to the west of 70°W, no statistically significant trends in the GS properties are found, consistent with the results based on in situ measurements. This result does not support a direct link of the sea level rise acceleration along the U.S. east coast with the GS slowdown, as has been argued in recent studies. However, it is possible that heat carried by the GS to the region causes these observed sea level changes.

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Revisited Sea Level Budget over 2005-2015 Indicates Large Deep Ocean Warming and Large Earth Energy Imbalance

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As the dominant reservoir of heat uptake in the climate system (93% of the total Earth heat uptake is located in the ocean [Levitus et al. 2012]), the ocean provides a critical measure of the Earth energy imbalance at the top of the Atmosphere. The ocean heat uptake can be inferred through the thermal expansion of the ocean estimated either directly from in situ Temperature profiles or indirectly with the sea level budget approach by combining satellite altimetry and GRACE observations. In this study we revisit the sea level budget approach and propose new estimates of the deep ocean warming and the Earth energy imbalance with reduced error bars (compared to previous studies such as Llovel et al. 2014). In previous studies GRACE and satellite altimetry observations have been estimated and combined in a reference frame centered on the center of figure of the Earth (CF). But GRACE and satellite altimeters move around the center of mass of the Earth (CM) and the projection of their observations in reference frames centered on the CF generates significant level of uncertainty in the data. In this study we combine for the first time new satellite altimetry products with new GRACE observations reprocessed with orbits centered on the CM. This approach enables to remove the source of uncertainty related to the projection on the CF and enables to test the sea level budget over the period 2005-2015 with unprecedented accuracy. This improved sea level budget approach indicates a important deep ocean warming of +0.42±0.4 wm-2 (at 1.65 sigma) and large Earth energy imbalance of 1.4±0.4 wm-2 (at 1.65 sigma) over the period 2005-2015.

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Impact of Recent ENSO Variability on Global and Regional Sea Level

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The impact of interannual to decadal variability on sea level has been heavily investigated in recent years. Particular focus has been put on the relationship between the El Nino-Southern Oscillation (ENSO) and interannual variability in global mean sea level (GMSL). The positive correlation between well-known ENSO indices and detrended GMSL has led to the attribution of many of the rises and falls in global sea levels to ENSO, with an over-generalization of the relationship often following. Several studies have linked the effect of ENSO on GMSL primarily to the movement of water between ocean and land, while others have highlighted a significant steric contribution that adds to the mass-related signal. Here, we adopt a more general technique, avoiding an index-based approach to find coupled modes of variability in modern observations of the different components of sea level change. Using such an approach, the impact of Pacific Ocean climate variability on GMSL can be quantified and separated into steric and mass contributions. Furthermore, interannual variability associated with ENSO can be preliminarily separated from lower frequency variability often attributed to the Pacific Decadal Oscillation (PDO). Closure is obtained in the global sea level budget on interannual to decadal timescales and used to explain the sharp recent increase in global sea level. Finally, this analysis highlights the varying conditions in the Pacific over the past few years from a sea level perspective.

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Land Processes and Inland Water#1: Lakes and Reservoirs

KEYNOTE: Aral Sea Evolution from Satellite Altimetry and other Remote Sensing Data

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Lakes are integrators of environmental changes occurring at regional to global scale and present a high variety of behaviors on a variety of time scales (cyclic and secular) depending on the climate conditions and their morphology. In addition their crucial importance as water stocks and retaining, given the sharp environment changes occurring worldwide at many anthropocentric levels, has increased the necessity of monitoring all its morphodynamics characteristics, say water level, surface (water contour) and volume. The satellite altimetry and satellite imagery together are now widely used for the calculation of lakes and reservoirs water storage changes worldwide. However strategies and algorithms to calculate these characteristics are not straightforward and need development of specific approaches. We intend to present a report of some of these methodologies by using the Syr Darya Basin and the Aral Sea to illustrate some critical aspects and issues (technical and scientific) linked with the survey of climate changes impacts on surface waters from remote sensing data.

Remote sensing data (radar altimetry and optical imagery) are used to highlight the potential of satellite data to monitor water resources: water height, areal extent and storage variations. New results from 25 years of monitoring using satellites over the Syrdarya basin and the Aral Sea are presented.

Since the early 1990s, radar altimetry has provided valuable information on water levels over rivers, lakes and reservoirs. Additionally, satellite imagery can be used to develop water contours, and if used in combination with radar altimetry data, allow estimation of inter-annual and seasonal water storage variations of lakes and reservoirs. It has been applied to the monitoring of reservoirs along the Syr Darya's upstream part, and to detect decadal term changes of Small Aral, South East and South West Aral. Data presented here are also available in the Hydroweb database: hydroweb.theia-land.fr.

From the beginning of the satellite radar altimetry era (i.e. 1978, with the launch of Seasat) until now, several missions have been used to calculate water level variations over lakes and rivers: Geosat, T/P, JASON-1, JASON-2, JASON-3, GFO, ENVISAT, ERS-2, Sentinel-3A, and SARAL/AltiKa. From now to the launch of the SWOT mission in 2021, time series obtained from historical data will be extended as a result of new missions S3B (2018), and JASON-CS (2019). Then, the wide swath interferometer onboard the SWOT satellite will allow coverage of the entire Earth with a hectometer resolution.

Satellite imagery, from low to high resolution (1km to few meters) offers a useful tool to monitor surface water extent over lakes or floodplains. There are many methods for the extraction of water surface from satellite imagery, which, according to the number of bands used, are generally divided into single-band and multi-band methods. In the simplest approach a single band is selected from a multispectral image and used to extract water surface information. MODIS data for example provide every 8 days, surface extension of free water, from 2000 to 2017, with a spatial resolution of 500 meters. It has been used to delineate the different water bodies, in particular floodplains and reservoirs where water extent has been precisely measured (Aydarkul, Toktogul, Karakul, Arnasay floodplain, Aral Sea).

Based on these different techniques we have determined the extent of water within the Aral Sea basin since 1993, as well as volume variations, which is key parameter in the understanding of hydrological regime in ungauged basin.

The accuracy of satellite data is 0.6 km3 using a combination of MODIS data and satellite altimetry, and only 0.2 km3 with Landsat images representing 2 to 4% of average annual reservoir volume variations in the reservoirs in the Syrdarya basin. With future missions such as Surface Water and Ocean Topography (SWOT), significant improvement is expected. The SWOT mission's main payload (a radar interferometer in Ka band) will furthermore provide 2-D maps of water height, reservoirs, lakes, rivers and floodplains, with a temporal resolution of 21 days. At the global scale, the

SWOT mission will cover reservoirs with areal extents greater than 250 by 250 m with 20 cm accuracy.

By complementing with in situ observations and hydrological modelling, space observations have the potential to improve significantly our understanding of hydrological processes at work in large river basins, (including water contained in lakes, reservoirs and floodplains) and their influence on climate variability and socio-economic life. Unprecedented information can be expected coupling models and surface observations with data from space, which offer global geographical coverage, good spatio-temporal sampling, continuous monitoring with time, and capability of measuring water mass change occurring at or below the surface.

Radar altimetry, coupled with complementary in situ data has allowed quantifying precisely the water balance of Aral Sea since 1993, but also to large reservoirs systems along Syr Darya

A focus on the Aral Sea and the reservoirs in the upstream part of the Syr Dayra over the last 25 years from satellite data is presented in this lecture, with some implications on the water balance. We will also describe the specific behaviour of South Aral west and East basins over the last 10 years

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Contribution of 25 Years of Satellite Radar Altimetry Towards Enhancing the Great Lakes Operational Forecasting System

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A constellation of multiple-platforms, multi-band active remote sensing satellites including all-weather sensors dedicated for scientific research are already operational or to be launched by space agencies including NASA, ESA, JAXA and industries. Many of these measurements are available at near real-time, and with different spatio-temporal resolutions/accuracies. Among these observations, notably multi-mission satellite radar altimetry spanning more than two and half decades, 1991–2018, including ERS-1/-2/Envisat, Geosat/GFO, TOPEX/Poseidon/Jason-1/-2/-3, SARAL/Altika, CryoSat-2, Sentinel-3, have been continuously measuring synoptically water level, wind, wave heights and potentially snow/lake ice extent series over the entire Great Lakes. The relatively novel ground-based Global Navigation Satellite System Reflectometry (GNSS-R) altimetry technique has been demonstrated to be capable of measuring off-shore water level, wind speed, and potentially lake ice thickness. This presentation reports early results of feasibility studies to use satellite altimetry and other satellite-based observations to improve Great Lakes monitoring, and to conduct data assimilative modeling experiments to assess their respective roles to potentially enhance the Great Lakes Operational Forecasting System.Radar altimetry, coupled with complementary in situ data has allowed quantifying precisely the water balance of Aral Sea since 1993, but also to large reservoirs systems along Syr Darya

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15-years Surface Water Storage Changes of Lakes and Reservoirs in Poyang Lake Basin Based on Multi-Spectral Imageries and Multi-Mission Radar Altimetry

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Poyang Lake is the largest freshwater lake of China, with a wetland which is China's largest and one of the seven wetlands in China designated as Wetlands of International Importance. The Poyang Lake Basin (PLB) is also one of the most productive agricultural areas primarily because of its flat terrain. However, the flat geomorphic feature of lake area and their direct connection with the Yangtze River make Poyang Lake very sensitive to the climate, ecologic and hydrologic changes. After 2002, the Lake has experienced several extreme low-water episodes, which are often attributed to the impoundment and operation of the Three Gorge Reservoir. Other reservoirs constructed near the PLB may be another factor for the water storage reduction in Poyang Lake. It is hard to explore the water storage variation in a large-scale as PLB through the traditional hydrological survey. The remotely sensed images provide a good data source at high spatial resolution to extract the water area variations, while the altimeters provide water height fluctuations. The MODIS 8-day surface reflectance products (MOD/MYD 09A and MOD/MYD 09Q) were used to delineate the water surface boundary. After the calculation of NDWI, the Otsu's automatic threshold extraction algorithm were applied in the remotely sensed image products to obtain the monthly water area variations of the 5 large lakes and 10 large reservoirs in PLB. Meanwhile, the multiple altimeter observations including T/P, ERS-1/-2/Envisat, ICESat, Jason-1/-2/-3, SARAL/AltiKa, Cryosat-2, and Sentinel-3 data were combined to derive the concurrent water level for the large lakes and reservoirs. Here we integrate MODIS imageries and multi-mission satellite altimetry to generate high-resolution lake-wide volume or storage change measurements via hypsometric techniques, 2002–2017, and then validate the results using in situ lake gauge data. It is evident that there is an uneven spatio-temporal patterns of the surface water storage changes in the lakes and reservoirs of PLB. We concluded that the accuracy of the altimeter water level height measurements achieved decimeter level. We then use the resulting water area-storage curve to calculate the storage change for the adjacent lakes and reservoirs in PLB which do not have altimeter nor gauge observations. The preliminary results reveal that the average seasonal water storage fluctuation for large lakes in PLB is more than 10 billion m³. The reservoirs in the basin show the similar magnitude of the water storage variation, but the seasonality characteristics is not so regular for its complicated operation rules. The annually averaged trends showed that the total surface water storage of large lakes and reservoirs had a stastistically significant small increase. Although the extreme low-water events in the Poyang Lake are correlated to the runoff increase caused by the anthropogenic lowering of Yangtze River channels and by climate change.

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Estimating 3-D Reservoir Bathymetry from Multi-Satellite Data

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This study presents and evaluates an automated method that rebuilds reservoir bathymetry by combining surface water extent and elevations derived from multi-satellites. The method has one parameter used to fix uncertainties introduced by water extent maps. A sensitivity analysis is performed over Lake Mead, USA, where ground-based bathymetric observations are available. Multiple sources of water level time series (Envisat/Altika and ground-based observations) are combined to a Landsat-based water extent database composed of 580 images over the 1985-2015 period. Results show a significant improvement in terms of RMSE when compared to bathymetry derived from another method based on the extrapolation of the digital elevation model. The new method is then applied to the Volta Lake, in Ghana, using MODIS-based water extent and results are discussed. We further combine the bathymetry with a DEM in a hydrological modeling framework in order to evaluate the impacts of reservoir operation on the Volta River dynamics.

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Lake Storage Variation on the Endorheic Tibetan Plateau and its Attribution to Climate Change since the New Millennium

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Alpine lakes in the interior of Tibet, the endorheic Changtang Plateau, serve as "sentinels" of regional climate change. Recent studies indicated that accelerated climate change has driven a widespread area expansion in lakes across the Changtang Plateau, but comprehensive and accurate quantifications of their storage changes are hitherto rare. Such volume estimate is crucial in understanding lake water budget and thus contributes to conclusively uncovering the dominant cause on lake dynamics in the complex alpine setting. This study integrated optical imagery (Landsat and Huangjing 1A/1B) and digital elevation models (SRTM and ASTER DEMs) to uncover the fine spatial details of lake water storage (LWS) changes across the Changtang Plateau at an annual timescale after the new millennium (from 2002 to 2015). The accuracy of our approach was compared with two existing approaches: one based on satellite imagery and long-term radar altimetry and the other based on satellite imagery and short-term ICESat (laser) altimetry. The result show that the proposed approach using DEMs outperforms that using ICESat altimetry by producing volume variations that are highly consistent with long-term radar altimetry record. The trajectory of net LWS across the Changtang Plateau exhibits three distinct phases: a monotonic increase from 2002 to 2012, a general cessation and pause in 2013 and 2014, and then an evident decline from 2015. Observations from the Gravity Recovery and Climate Experiment satellites (GRACE) reveal that the LWS pattern is in remarkable agreement with that of the regional mass changes: a net effect of precipitation minus evapotranspiration (P-ET) in endorheic basins. Despite some regional variations, P-ET explains ~70% of the net LWS gain from 2002 to 2012 and the entire LWS loss after 2013. These findings clearly suggest that the water budget from net precipitation (i.e., P-ET) dominates those of glacier melt and permafrost degradation, and thus acts as the primary contributor to recent lake area/volume variations in the endorheic Tibet.

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Cryosphere #1: Ice Sheet, Glaciers, Ice Cap

REVIEW: Understanding Drivers of Change in Antarctica's Ice Shelves from 25 years of Continuous Satellite Radar Altimetry

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Antarctic ice loss is accelerating and will soon become the largest contributor to sea-level rise. The Antarctic Ice shelves can provide mechanical support to “buttress” the seaward flow of grounded ice, so that ice-shelf thinning and retreat result in enhanced ice discharge to the ocean. Ice shelves are susceptible to changes in forcing from the atmosphere and the ocean, which both change on a broad range of timescales to modify mass gains and losses at the surface and base. The only viable way to monitor the full extent of the ice shelves while covering the main temporal scales of variability (e.g. interannual-to-decadal) is with satellites. We discuss results from satellite radar altimeter data from four ESA satellites (ERS-1, ERS-2, Envisat, CryoSat-2) to obtain time-series of ice-shelf surface height variations since the early 1990s. We focus on the variability present in the records, providing much more information that can be obtained from linear trends reported in prior studies. The continuous 25-year time series are sufficiently long to resolve patterns of multi-year variability linked to atmospheric and oceanic processes. We show examples of this analysis approach for two regions of Antarctica. The Pacific-sector ice shelves respond strongly to tropical ocean variability, with El Niño events increasing both snowfall and ocean-driven basal melting. The height increase by the added low-density snow exceeds the height decrease by loss of denser basal ice. But mass loss by this basal melting exceeds mass gain from snow, so ice shelves lose mass overall; the opposite occurs during La Niñas. On the Antarctic Peninsula, where several ice shelves have collapsed or significantly retreated in the last three decades, ice shelf heights have increased since 2009, in some cases recovering most of the declines reported previously. We connect this height recovery to reduced summertime melting of the surface, even as the ocean continues to melt the base and remove mass. We expect that the increased thickness of the surface snow layer will reduce the susceptibility of the ice shelf to surface-driven “hydrofracture”, which was linked to earlier collapses of peninsula ice shelves. These examples demonstrate the capability of long and continuous records from satellite altimeters; allowing us to improve our understanding of the mechanisms involved in ice-shelf changes to the point where we can confidently include this behaviour in models of ice-sheet response to climate changes.

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Net Retreat of Antarctic Grounding Lines Detected by CryoSat-2 Radar Altimetry

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Precise grounding-line locations are important observations for quantifying the discharge of marine-based ice sheets into the oceans, as indicators for the stability of an ice sheet, and as boundary conditions for numerical ice sheet models. Geological records document extensive grounding-line retreat during the deglaciation towards the Holocene in Antarctica. However, observations of Antarctic grounding-line migration during the satellite era remain scarce due to the lack of repeat satellite measurements. Here, we utilize observations of ice elevation change from CryoSat-2 satellite radar altimetry and measurements of the ice geometry to track the migration of Antarctic grounding lines, almost tripling the coverage of previous studies. We estimate that 10 per cent, 3 per cent, and 22 per cent of the Antarctic Peninsula, East Antarctic, and West Antarctic grounding lines, respectively, are retreating at rates faster than 25 m/yr, an average rate of retreat since the Last Glacial Maximum. The Antarctic Ice Sheet has lost over 200 square km/year of grounded ice area in the lifetime of CryoSat-2 on average. Previous studies have indicated that by far the fastest rates of retreat occurred in the Amundsen Sea Embayment. In contrast, we find that the Pine Island Glacier grounding line has stabilized since 2011-potentially as a consequence of abated ocean forcing. Finally, we report an intimate relationship between average ice thickness change at the grounding line and average rates of grounding line migration for fast-flowing ice streams in Antarctica indicating that the geometries of these ice streams are similar despite the various different processes involved in forming these.

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A Reconciled Estimate of Antarctic Peninsula Mass Balance

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During the satellite era, the Antarctic Peninsula has undergone dramatic environmental change, including ice shelf thinning (Shepherd et al., 2003; Paolo et al 2016) and collapse (Vaughan and Doake, 1996; de Angelis and Skvarca, 2003), accelerated glacier thinning and flow in the wake of ice shelf collapse (Scambos et al., 2004; Rignot et al., 2004), and widespread retreat of tidewater glaciers (Cook et al., 2005). These changes have major implications for the regional ice sheet mass balance, and the Antarctic Peninsulas contribution to present day global sea level rise. As the northern most point of the Antarctic continent, the peninsula experiences relatively warm atmospheric temperatures, and ocean temperatures have fluctuated due to incursions of circumpolar deep water onto the continental shelf. Consequently, the observed glaciological changes on the peninsula have been associated with both atmospheric and oceanic forcing. Here, we use 25 years of satellite altimetry to measure the detailed spatial pattern of change in ice surface elevation on the Antarctic Peninsula. We combine our continuous altimetry time series with gravimetry and velocity observations, to quantify the mass balance of the Antarctic Peninsula over the last 25 years. Mass balance estimates over the Antarctic Peninsula are challenging to make due to the mountainous terrain and locally variable glacier behaviour. To account for this, we tailored the individual techniques to the specific characteristics of the peninsula, and combined the estimates in such a way as to take advantage of their complementarity in coverage and resolution, thus increasing the confidence in our mass balance assessment of this difficult region. We find that between 1992 and the present day, the Antarctic Peninsula accounts for ~25% of the total Antarctic mass loss despite occupying only 4% of the total area.

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Dual Frequency Radar Altimetry-Measuring Greenland Firn Properties from Space

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For the last eight years, the ESA CryoSat-2 Ku-band radar altimeter has been measuring the elevation of the Greenland Ice Sheet. Ku-band enables surface penetration at firn covered areas, which hampers the direct interpretation of surface elevation change from Cryosat-2 and other Ku-band altimeters. However, mapping the changes in penetration depth can provide information on firn stratigraphy. If the physical surface (snow/air interface) of the ice sheet can be determined from an independent source, the differences in the two surfaces may directly be linked to the penetration depth of Ku-band radar altimetry, and hence to the temperature and density of the upper firn.

Here, we use independent estimates of the surface elevation changes from the Ka-band radar altimeter (AltiKa) operated onboard the French/Indian satellite SARAL. The higher frequency of Ka-band reduces surface penetration to a minimum and combining the records from both Ku- and Ka-band satellites are the key to utilizing the full potential of CryoSat-2. Hence, providing both high spatial-resolution surface elevation change and insights into changes in firn properties. The interpretation of dual-frequency altimetry is supported by firn modeling. The model has previously been applied to gain mass balance from ICESat and is now updated with a conceptual model for Ku-band radar penetration. Ultimately, a dual-band radar altimeter operating from space may provide ice sheet wide measurements of firn densities, a key parameter in determining direct ice mass balance from satellite altimetry.

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Contribution of Satellite Radar Altimetry towards Quantifying Present-Day Mass Balance Estimates for Mountain Glaciers and Ice Caps

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The 2013 Intergovernmental Panel for Climate Assessment (IPCC) Fifth Assessment Report (AR5) concluded that the observed and explained geophysical causes of global geocentric sea-level rise, 1993–2010, is much closer towards closure (COMPARED TO PREVIOUS REPORT?). However, the discrepancy reveals that up to approximately 30% of the observed sea-level rise remains unexplained, despite contemporary reports on reconciled mass balance estimates of ice-sheets and mountain glaciers during the early 21st century. This discrepancy is primarily attributable to the wide range of estimates of respective contributions of the Greenland and Antarctic ice-sheets, mountain glaciers and ice caps to sea-level rise. In particular, the High Mountain Asian glacier systems remains a focus of public and scientific debate, as the uncertainty of its mass balance estimates and its future projection have a significant implication of water resource problems affecting 1.5 billion people in the region. It is also not clear, in the case of the High Mountain Asia glacier system that glacier ablation would instantaneously contribute to sea-level rise, as the majority of melt water is used for anthropogenic activities in the region before it reaches the ocean. In this paper, we provide an updated estimate of mass balance of mountain glaciers and ice caps, and their respective contributions to global sea-level rise. We further assess the contribution of satellite altimetry data including ICESat and CryoSat-2, and compare results with GRACE gravimetry and in situ mass balance data.

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Open Ocean #2: Tides, Internal Tides, Internal Waves

REVIEW: Progress and Challenges of the Tide Correction for Altimetry over Last 25 Years

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Thanks to its current accuracy and maturity, altimetry is considered as a fully operational observing system dedicated to various applications such as climate studies. Altimeter measurements are corrected from several geophysical parameters in order to isolate the oceanic variability and the tide correction is one of the most critical.

Global tide models GOT and FES are commonly used as a reference for tide correction in actual altimeter GDRs. GOT model is an empirical model based on altimeter data, while FES is a finite elements hydrodynamic model which assimilates altimeter and in situ data.

The accuracy of tidal models has been much improved for last 25 years leading to centimetric accuracy in the open ocean. However significant errors still remain mainly in shallow waters and in polar regions, due to the omission of compound tides, to bathymetric errors, to sea ice effects ... New global tidal models have been developed recently showing a great improvement of accuracy even in shallow water areas and in Arctic regions. These new models take advantage of the very long altimeter time series now available, which represent an unprecedented global ocean database. We propose to give an overview of the evolution of the FES tidal model over last 25 years of altimetry, and to introduce the new challenges of the tide correction for space altimetry and gravimetry. In addition, we will present the consecutive progress in tide-related science applications (geodesy, earth rotation, etc…).

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KEYNOTE: Internal Tides: the View from Satellite Altimetry

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The 1996 discovery of internal-tide signals in Topex/Poseidon satellite altimetry was unexpected and surprising for a number of reasons, including: (i) that altimetry could detect such a tiny surface signal and that it could be properly interpreted, (ii) that such signals could remain phase-locked to the astronomical tidal potential over many years, (iii) that such waves could travel coherently thousands of km across wide expanses of the ocean. Altimetry was seen to have opened up a new avenue for studying an ocean phenomenon that had been previously limited to sparse in-situ measurements. Progress was fairly slow at first, owing to fundamental limitations of altimetry: inadequate temporal sampling along tracks spaced too far apart. Since mode-1 semidiurnal tides have typical wavelengths of order 100 km, first attempts to map wave properties (e.g., energy fluxes) led to overly blurred charts.

Many years of multi-mission altimetry have helped clarify our picture of low-mode internal tides in the deep ocean. Roughly speaking, about half of the mode-1 tidal variance can be called stationary--and is thus fairly predictable---and about half is non-stationary. Little of the mode-2 energy is stationary. Mapping only the stationary waves misses most of the internal-tide energy in the equatorial Pacific and Indian Oceans. There is little coherent tidal signal in regions of strong boundary currents, but the ocean may well contain no coherent tides in these regions. In some places (e.g., the South China Sea) there is strong seasonality that has been mapped with altimetry. Some of this seasonality can be directly related to changes in ocean stratification. In a few intriguing places, internal-tide changes are directly related to stratification changes that have been measured by Argo floats, suggesting a new technique for monitoring ocean heat content with altimetry.

Maps are now being developed of the energy fluxes of coherent internal tides in deep water. Crude maps of energy flux divergence are helping reveal sources and sinks of internal tides, but there is as of yet no way to distinguish between loss of coherence and wave dissipation. This mapping is critical to helping resolve the role of internal tides in ocean mixing and in developing parameterizations that can be used in ocean climate models. Non-stationarity considerably complicates these endeavors.

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REVIEW: A Review of Global Internal Tide and Wave Modeling

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We review the progress made in the last 15 years on global modeling of internal tides and the internal gravity wave continuum spectrum. In recent years, some high-resolution ("eddying") global ocean general circulation model simulations have begun to include astronomical tidal forcing as well as atmospheric wind and buoyancy forcing. Models with simultaneous tidal and astronomical forcing are capable of resolving an internal tide field with a realistic amount of non-stationarity, and a partial internal gravity wave continuum spectrum. Global internal tide and internal gravity wave models are important for interpreting satellite altimetry, and for other operational oceanographical considerations. Here we describe the most important technical details behind global internal tide and internal gravity wave models, including tidal forcing, topographic internal wave drag, self-attraction and loading, and the need for and constraints on high horizontal and vertical resolution. We focus on simulations of the HYbrid Coordinate Ocean Model (HYCOM) and the Massachusetts Institute of Technology general circulation model (MITgcm). We compare the modeled internal tides and internal gravity wave continuum to satellite altimeter observations and in-situ observational records. We discuss our early applications of a Kalman filter to improve the accuracy of the modeled barotropic tides. We discuss the challenges of, and progress made in, modeling stationary and nonstationary internal tides, and the internal gravity wave continuum spectrum, especially with respect to applications for satellite altimetry.

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REVIEW: A Review of New Internal-Tides Models and Validation Results

Carrere L.[1], Lyard F.[2], Baghi R.[1], Picot N.[3], Arbic B.[4], Dushaw B.,[5] Egbert G.[6], Erofeeva S.[6], Ray R.[7], Ubelmann C.[1,] Zaron E.[8], Zhao Z.[9], Buijsman M.[10], Richman J.[11], Schriver J.[12]

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With its current accuracy and maturity, altimetry is considered as a fully operational observing system dedicated to scientific and operational applications. In order to access the targeted ocean signal, altimeter measurements are corrected for several geophysical parameters. The ocean tide correction is one of the most critical of these parameters. Global ocean and loading tide models GOT and FES are operationally used in present altimeter GDRs. These global ocean tide model are barotropic models, however, and they do not include the surface signatures of internal tides.

Indeed internal tides can have a signature of several cm at the surface with wavelength ranging 50-250 km for the lowest three modes. From the perspective of SWOT mission and high-resolution ocean measurements, removing these small scale signals is a challenge, since we need to be able to separate all tide signals from other oceanic variability (mesoscale, sub-mesoscale …).

In this context, several scientific teams are working on the development of new internal tides models (Egbert and Erofeeva 2015, Ray and Zaron 2016, Zaron 2016, Zhao et al. 2016, Dushaw 2015, Shriver et al. 2014, Ubelmann personal communication), taking advantage of the very long altimeter time series now available, which represent an unprecedented valuable global ocean database. The internal tide models presented here are of three types: empirical models based upon analysis of existing altimeter missions, usually more than one, assimilative models based upon assimilating altimeter-derived internal tide fields into a reduced gravity model, and three-dimensional models, that embed internal tides into an eddying general circulation model.

Recently, a detailed comparison and validation of these available models has been conducted to determine their impact on the altimeter measurement accuracy. The analysis focuses on the correction of the coherent internal tide signal for the main tidal constituents. The validation process is based on a statistical analysis and on a comparison to multi-mission altimetry including Jason-2, AltiKa and Cryosat-2 data, taking advantage of the various and long-term altimeter databases available. We propose to present the results of this internal-tides models comparison. We will also introduce new improvements under development.

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Land Processes and Inland Water #2: Methods and Rivers

Benefits of the Open Loop Tracking Command (OLTC): Extending Conventional Nadir Altimetry to Inland Water Monitoring

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In the past 25 years, radar altimeters have been designed and operated primarily for ocean observation. However, over the past decade there has been a growing interest for altimetry measurements over inland waters. Studying lakes, reservoirs and rivers water level is of prime importance for the hydrology community to assess the Earth's global resources of fresh water.

Altimetry is key to provide such global and continuous datasets of water surface height. Indeed, much progress has been made in altimeters capability to acquire quality measurements over inland waters.

We present an overview of major technical evolutions of the tracking function of altimeters, from Jason-2/POS3 and SARAL/AltiKa to Jason-3/POS3B and Sentinel-3/SRAL and the improvements brought by the open loop tracking command (OLTC) to extend the altimeter observation domain to inland waters.

We show how Jason-3 and Sentinel-3 altimetry missions are currently able to observe and monitor thousands of lakes and rivers all over the globe and how it is contributing in building a global dataset of inland waters level, in preparation for future missions such as Sentinel-6 and SWOT

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Implications of Specular Echoes for Monitoring of Inland Water Bodies

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In a 2017 paper [1] the authors report that for rivers of small to moderate width (<300m) the radar altimeter echoes are often near specular. Specularity implies that surface roughness is << λ.

The symposium paper will summarize and expand on this publication, with particular regard to implications for future inland water monitoring.

Doppler processing is especially suitable for specular echoes. Egido and Smith [2] introduced the "focused SAR" algorithm for a point specular reflector (with example shown for a very small pond). Our paper generalizes focused SAR to extended, irregular shaped water bodies, e.g., a meandering river or irregular shaped lake. The complex radar echo waveform is modeled as the sum of all elemental scatterers on the water surface. The shape and location of the water surface, determined from a high resolution optical image, is the input into the model. The water level is the unknown model parameter and is found by adjusting the model complex waveform to match the actual complex altimeter data echoes. This method is shown to produce water level accuracy on the order of millimeters in a single pass.

The paper characterizes the complex waveform in echo number – range gate space (i.e. a complex radargram). It is not actually a hyperbola as often assumed for specular echoes. Only a point specular is exact hyperbola. For extended surfaces the hyperbola flattens for a duration when the radar nadir runs over the water surface. This is an important consideration to achieve the greatest accuracy in water level.

Radar altimetry echoes of several actual rivers were compared with model predictions. (Three examples are shown in [1]; for the conference we will demonstrate generality by more examples.) There is also an example of specular echoes from a pass over a flood plain to measure the local geoidal perturbation.

One implication of specular echoes is that very small rivers (~20 m wide) can be measured without land interference. The water level is measured with just 1st contact range gates, which are either entirely free of land backscatter or at least 40 dB above nearby land backscatter. Unfortunately another implication of specularity is that water is detected for only a short track interval, and only when the water is at or very near nadir. The extent of water detection varies with the water body dimensions, but is typically a few hundred meters to one km. This conclusion runs contrary to the assumed 120 km swath in the SWOT mission.

After publication of [1] we extended the specularity model to include local surface slope as an additional free model parameter. We demonstrate measurement of ~1cm/km slope with noise free simulation. Further analysis in progress to determine whether or not noise will be a limiting factor in slope measurement.

[1] Abileah, Scozzari, Vignudelli, (2017). Envisat RA-2 Individual Echoes: A Unique Dataset for a Better Understanding of Inland Water Altimetry Potentialities. Remote Sensing, 9(6), 605.

[2] Egido, Smith. 2017. Fully Focused SAR Altimetry: Theory and Applications. IEEE Trans. Geosci. Remote Sens., 55, 392–406

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Improvements Brought by Updated Water Masks onto Altimetric Measurements over Rivers

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Previous works at ALONG-TRACK have lead to the selection of a water mapping algorithm that has been applied to Sentinel-1 SAR images to obtain water masks at various dates. The objective is to use the water masks data base within the Sentinel-3 Hydrologic Altimetry Processor prototypE (SHAPE). In this ESA funded project under the SEOM Programme Element, we are testing, among other things, the real benefit of selecting, 'on the fly', the mask that is the closely codated with the SAR altimetric data. If such a versatile approach brings a sufficient improvement and robustness it will replace the old approach based on a 'static' water mask (SRTM SWBD). In this project we consider both Sentinel-1 and CryoSat-2 data (at the time of writing this abstract) but we could extend it to Sentinel-3.

The water mask is currently used for two purposes :

• Perform geographical selection of the records so as to keep those over water to produce the water level time series ;

• Compute a Water Fraction field as an auxiliary data to the altimetric level 2 products. This may help 1. the final users to build time-series or select a subset of the measurement dataset, 2. the specialists to analyse SAR retrackers performances, 3. us to re-run a Stacks / Waveforms characterisation we tested in the past [Fabry et al. 2016c] based on CryoSat-2 data and the old static SRTM SWBD that was outdated.

This work, performed under ESA funding, not only highlights the great synergy potential of the Sentinel-1, and 3 missions to improve the inland water SAR altimetry processing, but also opens up the door to improvements in SAR alti-hydrology. It could be replicated to LRM altimetry missions and the concomitant imagers as well. Improving Water Level time series will permit assimilation into models such as HYPE to produce improved Water Discharge. This is one of the main objectives of the SHAPE project.

[Fabry et al. 2016c] – Fabry P., Bercher N., Roca M., Garcia Mondejar A., Restano M., Ambrózio A., Benveniste J. (2016). « Characterization of SAR Mode Altimetry Data over Inland Waters – SHAPE project », Oral communication, October 31 – November 4, Espace Encan, La Rochelle, France.

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Multi-Mission Based River Levels

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Rivers levels typically show large seasonal variations. In Arctic rivers, the water level rises rather quickly in the spring when the snow and ice are melting. This abrupt rise is challenging to capture for missions such as Sentinel-3 and SARAL/AltiKa that has a repeat period of approximately one month. However, by combining levels from several missions the temporal resolution is significantly improved.

Here we use data from CryoSat-2, SARAL/AltiKa, and Sentinel-3A for a river segment to make a joint solution of the river level. We set up a model that consists of state-space model and two spline functions. The state-space model is composed of an AR1 process and an observational part, where the error follows a mixture between normal and Cauchy distributions. The spline functions account for the change in topography and a potential variation in water level amplitude along the river. We demonstrate the model for the Ob River and other selected Arctic rivers.

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Evaluating Multiple-Mission Satellite Altimetry towards Establishing a Long-term Climate Record of Poorly–Gauged Rivers in Indonesian Borneo

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We study several poorly-gauged rivers in Indonesian Borneo using over 25 years of satellite radar altimeter data to measure river water elevation as a long-term climate data record. The rivers we studied are considered small to medium since their widths vary between 40 to 400 meters. We use limited in-situ gauge data from year 2007 to 2017 to evaluate the performance of multiple satellite altimetry missions, i.e. ENVISAT, SARAL/AltiKa and the most recent European Space Agency mission Sentinel-3. In some rivers we also use the measurements from NASA/CNES Jason-2/-3 satellite altimetry missions. Remote sensing imageries and geospatial information are used to mask the water bodies. Prior to range measurements data processing, we apply semi-automatic waveform shape filtering with machine learning approach to filter the range measurement dataset based on waveform shapes that conform to inland water signature. Standard waveform retracking is then applied to each of the multi-mission satellite altimetry range measurements. The corresponding re-tracked range were then being processed to infer the rivers' water surface elevation. We computed the Root Mean Square Error (RMSE) statistics to evaluate the performance of data set from each satellite altimetry missions. The results of this study is essential to help local government monitor the rivers, especially those that are not properly gauged or when the gauge is very limited in numbers and distribution.

This study is part of a research program that provide a way to monitor Indonesian Borneo rivers' water surface elevation and assimilating the satellite altimetry-based water surface elevation data along with regional discharge estimation from hydrologic model, which is also built using satellite-based precipitation estimation.

Keywords: satellite altimetry, river, waveform, retracking, Borneo

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Cryosphere #2: Sea Ice and Polar Oceanography

REVIEW: 15 Year Climate Data Record of Arctic Sea Ice Thickness from Two Generations of Satellite Radar Altimeters

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Sea ice thickness is one key indicator to understand the causes and consequences of Arctic Change. Climate data records (CDR's) of Arctic sea ice thickness (SIT) with sufficient length are therefore highly anticipated to complement other sub-variables of the essential climate variable (ECV) sea ice, such as concentration, area and extent. While the CryoSat-2 mission was pivotal for establishing routine sea-ice thickness retrieval from satellite altimetry since 2010, its current data record is still too short to separate climate trends from inter-annual thickness variability in the Arctic. Significant efforts have therefore been made to extent the SIT CDR by using CryoSat's radar altimeter predecessor Envisat (2002-2012). The evolution from the pulse-limited radar altimeter RA-2 on Envisat to the SAR altimeter SIRAL onboard CryoSat-2 and the subsequent improvement in footprint size however poses a significant challenge for maintaining stability of the 15 year long SIT CDR. One issue linked to the radar altimeter type is preferential sampling for mixed surface types which are more often encountered in the larger Envisat footprint. A separate challenge is the required stability of auxiliary parameters such as snow depth on sea ice and ice density that are required for the conversion of the freeboard measurement of the altimeter into sea ice thickness.

We discuss results and error characterization for both generations of radar altimeter systems as well as strategies to mitigate intermission biases that have been developed within the framework of the ESA Climate Change Initiative on Sea Ice. From 2018 on, the continuation of the SIT CDR will be ensured by the Copernicus Climate Change Service (C3S). We will present plans to extend the SIT CDR into the past using the ERS-1/2 missions or beyond the lifetime of CryoSat-2 with the Sentinel-3 constellation. We will also outline requirements for future evolutions in satellite radar altimetry, such as the potential Polar Ice and Snow Topography mission, to both maintain the SIT CDR and evolve SIT retrieval using satellite radar altimetry.

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Arctic Sea Ice Floe Size and Thickness Distributions from Multi-decadal Satellite Radar Altimeter Measurements

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Multi-decadal observations of sea ice thickness, in addition to those available for extent, are key to understanding long-term changes in the amount of Arctic sea ice. The European Space Agency's (ESA) ERS-1, ERS-2, Envisat and CryoSat-2 satellite radar altimeter missions provide a continuous 25-year (1993-present) dataset with the potential to estimate Arctic sea ice thickness up to 81.5°N. However, differences in the satellite spatial resolutions will cause discrepancies in their surface type discrimination over sea ice regions. This will lead to differences in the sea ice floe size distribution and subsequent freeboard and thickness estimates from the missions. Here we focus on geometric sampling differences between Envisat and CryoSat-2 by assessing their lead densities and sea ice floe size and thickness distributions during their overlap period of November 2010-March 2012. We find that Envisat preferentially samples wider, thicker sea ice floes leading to a thickness bias between Envisat and CryoSat-2 of 77 cm over first year ice and 22 cm over multiyear ice. Accounting for this geometric sampling bias provides a new, physically-based approach to bias correction that differs from currently existing empirical solutions dependent on waveform shape. Our bias correction will enable us to produce a 15-year time series of Arctic sea ice thickness in the seasonal ice zone and can be extended to past missions such as ERS-1 and -2, the current Sentinel-3 mission, and future satellite radar altimeters.

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Arctic Icebergs Climatology 1992-Present from Altimeter Data

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Conventional pulse limited (LRM) altimetry is a powerful tool to detect and characterize small (<10km²) icebergs (Tournadre et al 2007, 2012). Since 2015, the ALTIBERG project processes the archives of all altimeters and maintains a data base of small icebergs and ice volume distributed through the CERSAT website (http://cersat.ifremer.fr/user-community/news/item/473-altiberg-a-database-for-small-icebergs). Up to now this database was limited to the Southern Ocean. Taking advantage of the re-processing (version-2) of the Altiberg database we extended the coverage to the Northern Hemisphere especially around Greenland and within the Baffin Sea.

Compared to the Southern Ocean where a large portion of the region covered by icebergs is located north of 66°S, i.e. it is sampled by the Topex-Jason altimeter series, the Northern Hemisphere icebergs are located mainly north of 66°N. The number of altimeters available at a given time is thus more limited than that in the Southern Hemisphere. Furthermore, the coasts of Greenland are characterized by a extremely large numbers of small islands and rocks that can be mistaken for icebergs. These small land features are not well represented even in the high resolution land masks. A tedious work of detection and control of those rocks and islands had to be conducted to create a database used to flag the detected targets to eliminate land contamination. The archive of 11 altimeters have been processed to create a Northern Hemisphere data base. Great care has thus been taken to inter-calibrate the different altimeters to insure the homogeneity and continuity of the time series. As for the Southern Hemisphere, the monthly mean probability of presence, the mean area of icebergs and the mean volume of ice have been computed on a regular polar grid.

The distribution of icebergs reflects the ocean circulation around Greenland. It mainly follows the East and West Greenland Currents along the coast of Greenland and the Baffin Current within the Baffin Bay. The analysis of the total volume of ice shows a constant increase of the volume of ice of icebergs from 1992 to 2017 that reflects the increase of the ice loss of the Greenland Ice sheet.

Tournadre Jean (2007). Notes and correspondence-Signature of lighthouses, ships, and small islands in altimeter waveforms . Journal of Atmospheric and Oceanic Technology, 24(6), 1143-1149 .

Tournadre Jean, Ardhuin Fanny, Legresy Benoit (2012). Antarctic icebergs distributions, 2002-2010 . Journal Of Geophysical Research-oceans, 117(C05004), 15 pp.

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Sea Level and Ocean Circulation in the Ice-Covered Polar Oceans: Variability, Change and Implications for Climate

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Historically, sea level is poorly observed in the polar oceans due to a lack of tide gauge records, poor coverage by conventional altimeters, and because large areas are perpetually or seasonally ice-covered. However, specialized processing techniques to retrieve sea level from openings in the sea ice cover has allowed us to develop monthly sea level composites of the ice-covered and ice-free ocean in both the Arctic and Southern Oceans. This has led to scientific advances in our understanding of sea level and upper ocean circulation variability in these climatically important regions.

In the Arctic, sea level variability is dominated by a strong seasonal signal associated with seasonal freshwater fluxes, while decadal changes reflect globally significant freshwater accumulation in the Beaufort Gyre, the dominant surface circulation feature of the Western Arctic Ocean. This additional volume of freshwater has the potential to provide a climatically significant perturbation to the convective overturning of the North Atlantic if released. Increases in upper ocean currents are shown to play a role in modulating freshwater accumulation, and in dissipating oceanic kinetic energy by 'rubbing' against sea ice, while overall the Arctic Ocean has become more energetic as sea ice is lost.

In the marginal seas of Antarctica, the Antarctic Slope Current (ASC) system is revealed to be an almost circumpolar feature, that is seasonally strongest in autumn. Month-to-month circulation variability in the Ross and Weddell Gyres is modulated by the local wind stress curl, which in turn is weakly correlated with the Southern Annular Mode (SAM). During the 2015-16 El Niño, there were sustained negative coastal sea level anomalies, implying a weakening of the ASC, and potentially a shoaling of warmer water and increased oceanic heat delivery to the cavities of West Antarctic ice shelves.

These novel altimetry data provide a unique look at these data-sparse regions, providing the first pictures of monthly to decadal variability in the polar oceans and their coupling to atmospheric forcing. Continuing to monitor the polar oceans with satellite altimetry will provide invaluable observations of how the high latitudes are adjusting under climate change.

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Exploring the Synergy of Sea Surface Height, Ocean Bottom Pressure, and Sea Surface Salinity to Study Arctic Ocean Freshwater Changes

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The Arctic Ocean freshwater content and distribution are changing due to the combined effects of river runoff, precipitation, sea ice melt, and wind-driven ocean circulation. These changes can impact the North Atlantic Ocean circulation and the related transports of heat, freshwater, carbon, and nutrients that have potential influence on climate, weather and water and biogeochemistry cycles.

In this study, we first analyze the complementarity of sea surface height (SSH) anomaly, ocean bottom pressure (OBP), and sea surface salinity (SSS) to characterize the Arctic Ocean freshwater content and distribution. SSH-OBP anomalies reflect changes in steric height, which is dominated by halosteric (freshwater or salinity) changes in the Arctic Ocean. We then explore the utility of SSH from satellite altimetry and OBP from satellite gravimetry to evaluate satellite SSS. In regions where SSS changes are indicative of column-integrated halosteric height variations, satellite observations of SSH-OBP can be used to evaluate satellite SSS. In the past several years, three satellite missions (SMOS, Aquarius, and SMAP) have been providing synoptic measurements of sea surface salinity (SSS) over the global oceans. Nevertheless, these measurements are subject to relatively large uncertainties in high-latitude oceans due to the poor sensitivity of the L-band sensors to salinity in cold-water environment. Moreover, the paucity of in-situ salinity observations in the Arctic Ocean poses a challenge for evaluating the satellite SSS. We present an assessment of the quality of the different satellite SSS products using satellite-derived SSH-OBP data.

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Open Ocean #3: Mesoscale–Smaller-Scale Currents

REVIEW: How Our Understanding of Ocean Mesoscale Eddies Has Evolved over 25 Years

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Twenty-five years ago, our understanding of ocean mesoscale eddies was in its infancy, with recent progress on the global distribution of eddy energy and fluxes made available from Seasat and Geosat satellite altimeters. Since 1992, we have had a minimum of 2 and up to 5 altimeter missions making global observations of ocean sea level and its variations, bringing unprecedented coverage of the ocean mesoscale eddy field and its seasonal, interannual and decadal variations. We will review some of the recent analyses of mesoscale variability based on this long term time series. The improved alongtrack data from multiple altimeter missions allows a better representation of the smaller-scale eddy structures, and spectral analyses of these alongtrack data have revealed the regional variations in altimetric noise and eddy turbulent cascades. Most mesoscale eddy studies have relied on the 2D multi-mission mapped data, which reveals the rich structure of the larger mesoscale eddies and jets, and how they evolve in time and space, and in relation to the larger-scale circulation changes. We will address the recent progress in estimating eddy fluxes, eddy diffusion and Lagrangian particle tracking and statistics based on the mapped data.

In parallel, the in-situ observations within mesoscale eddies have evolved from having a few detailed process studies, to long term monitoring in a few regions, and a large-scale data base of Argo floats collocated with mesoscale eddies. Altimetry provides the depth-integrated view of the mesoscale eddy field, and we will review the recent progress in combining altimetry with in-situ observations to better define the eddy vertical structure. Coupled ocean-atmospheric processes are also impacted by mesoscale eddies and are being explored in joint analyses using altimetry, wind and SST fields, as well as models.

Reprocessing of the conventional and SAR alongtrack altimetry now reveals smaller scale eddy processes, but via a 1-D slice across the 2-D turbulent field. In the future, the wide-swath SWOT mission to be launched in 2021 will provide the first 2D observations of the smaller ocean eddy SSH field. We will present some new ideas in creating 2-D maps that aim to retain more of the smaller-scale eddy features, from today's alongtrack data and the future SWOT data. These smaller-scale sea surface height altimetric data also include aliased high-frequency internal tide and internal wave structures. A new challenge and opportunity for our community is to understand how these high-frequency motions impact and interact with the observed smaller mesoscale eddy field, based on today's altimetry and models.

Morrow, R., L.-L. Fu, J.T. Farrar, H. Seo and P.Y. Le Traon, 2018. "Ocean eddies and mesoscale variability". In "Satellite altimetry over oceans and land surfaces" CRC Press, Taylor and Francis

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REVIEW: A Review of 30 Years of Advances in Rossby Wave Theory Prompted by Satellite Altimetry

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The existence of Rossby waves in the ocean and atmosphere was established theoretically over 60 years ago by Carl Gustav Rossby. While such waves had been routinely observed in the atmosphere following their theoretical discovery, it is only with the advent of satellite altimetry and the landmark publication by Chelton & Schlax (1996) that the ubiquity of such waves in the ocean was finally established. Or so we thought. Indeed, owing to the relatively poor spatial resolution of the early satellite altimeter data, the observed westward propagating signals were initially interpreted as the signature of first-mode baroclinic Rossby waves propagating 'too-fast' as compared to the standard linear flat-bottom theory. Subsequently, however, the increased spatial resolution afforded by multi-missions led Chelton & al. (2007) to revisit their initial assessment and to conclude that what Chelton & Schlax (1996) had previously interpreted as linear waves should actually be interpreted as nonlinear meso-scale eddies. Regardless, Chelton & Schlax (1996) proved nevertheless extraordinarily influential in prompting new developments in Rossby wave theory, and in resuscitating older theoretical results that had not necessarily received much attention for lack of available observations to test or refute them. The main aim of this talk will be to review the theoretical developments in Rossby wave theory prompted by the development of satellite altimetry over the past 30 years, and discuss the implications of Chelton & al (2007) results for the future developments of the theory.

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REVIEW: Overview of Fine-scale Multiplatform Experiments in the Southwest Mediterranean Sea: Lessons Learnt in the Last Five Years

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This study is a review of recent high-resolution multiplatform experiments performed in the SouthWest Mediterranean Sea with the goals of (1) improving our understanding of submesoscale dynamics and interactions at the mesoscale and (2) identifying advances and limitations of present and future altimetry constellations.

After a brief overview of AlborEx, a multi-disciplinary process study conducted in the eastern Alboran Sea in 2014, we will present an evaluation of Sentinel-3A. An experiment was undertaken in the Algerian Basin in May 2016, employing an ocean glider and a ship mission with ADCP, along the same track and synchronous with an overpass of the Sentinel-3A mission. This provided three independent views of the ocean velocity field, along a section that encompassed three different oceanographic regimes. The results demonstrate the capacity of Sentinel-3A to retrieve fine-scale oceanographic features (~20 km). The intercomparison with in situ platforms showed a significant improvement, order 30% in resolution and 42% in velocity accuracy using a synthetic aperture radar mode with respect to lower-resolution mode of conventional altimetry. In addition, the three-platform view provided valuable insight into the variability of evolving oceanographic features, in an area of the Mediterranean that remains chronically under sampled. A summary of the results of IRENE, carried out in July 2017 in the Almeria-Oran front, will be also presented. IRENE is a pilot experiment of CALYPSO, a new Office of Naval Research (ONR) Departamental Research Iniative that aims to advance the state of science for theoretical, observational and numerical understanding of vertical transport on a range of scales.

In the second part of the presentation, we will focus on the PRE-SWOT cruise, which will take place in May 2018 in the southern region of the Balearic Islands onboard R/V García del Cid. PRE-SWOT aims at anticipating the daily high-resolution 2D SSH fields that SWOT will provide during the fast sampling phase after launch in selected areas of the global ocean; one of them being the region around the Balearic Islands. Special attention will be devoted to separate the scales typically resolved by the present altimeter gridded products compared to the scales that will be observed by SWOT and lead the observations of vertical transports associated with fine-scale features. In situ systems, including gliders, drifters, CTD, ADCP, and water samples, will be used in synergy with satellite data and modeling simulations to determine physical and biochemical ocean variability. This experiment will contribute to the preparatory SWOT cal/val activities and will be coordinated with the French BIOSWOT cruise.

We will conclude with the lessons learnt during the last 5 years in terms of advantages and limitations of synergetic approaches combining satellite altimetry with other cutting-edge and well established observational techniques and numerial modeling. Future directions of research will be also addressed.

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Decadal Mesoscale Eddy Modulations in the Western North Pacific Subtropical Gyre

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Satellite altimeter data of the past 25 years are used to investigate the low-frequency mesoscale eddy variability inside the western North Pacific subtropical gyre. Eddy activity modulations with a decadal timescale are detected concurrently within the 18-28N band, including the three branches of the Subtropical Countercurrent (STCC) and the Hawaiian Lee Countercurrent (HLCC). Lagging behind the Pacific decadal oscillation (PDO) index by six month, enhanced eddy activities were detected in 1995-98, 2003-06, and 2015-2017, whereas the eddy activities were below the average in 1999-2002 and 2009-14. Analysis of the temperature and salinity data that became available after 2001 via the International Argo Program reveals that the modulating eddy activities are due to the decadal change in the upper ocean eastward shear in the broad-scale STCC/HLCC band. By conducting an upper ocean temperature budget analysis, we found that this observed eastward shear change can be effectively accounted for by the decadally-varying surface heat flux forcing. Using the Argo-based temperature and salinity data, it is further found that the decadal subsurface potential vorticity (PV) signals to the north and beneath the STCC/HLCC were vertically coherent and not confined to the mode water isopycnals. Adjusting to the PDO-related surface forcing, these subsurface PV anomalies lagged behind the upper ocean eastward shear signals and likely made minor contributions to generate the decadally-varying eddy signals observed in the western North Pacific subtropical gyre.

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Characterizing the Transition from Balanced to Unbalanced Motions in the Southern California Current System

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As observations and numerical models improve their resolution of oceanic motions at ever finer horizontal scales, interest has grown in characterizing the transition from the geostrophically-balanced flows that dominate at large scales to submesoscale turbulence and waves that dominate at small scales. In this study we examine the mesoscale-to-submesoscale (100 km to 10 km) transition in an eastern boundary current, the southern California Current System (CCS), using repeated shipboard acoustic Doppler current profiler (ADCP) transects, high-resolution along-track nadir altimetry (processed Jason data from ALES, the Adaptive Leading Edge Subwaveform tracker), and one year of MITgcm simulations from a 1/48º global model with embedded tides. In the CCS, the submesoscale is as energetic as in western boundary current (WBC) regions, but the mesoscale is much weaker, and as a result the transition lacks the discernible change in kinetic energy spectral slope observed for WBCs. Helmholtz and vortex-wave decompositions of the kinetic energy spectrum are used to identify balanced and unbalanced contributions, since spectral slope alone does not distinguish them. At horizontal scales greater than 70 km, we find that the kinetic energy is dominated by balanced geostrophic motions. At scales from 40 km to 10 km, unbalanced contributions such as inertia-gravity waves contribute nearly equally as balanced motions. The model results indicate that surface-layer submesoscale turbulence and inertia-gravity waves undergo seasonal cycles of opposing phase, with submesoscale turbulence peaking in late winter/early spring and inertia-gravity waves peaking in late summer/early fall. The phase cancellation results in kinetic energy spectra that exhibit only weak seasonality, consistent with in situ observations. Our results suggest that the limit on diagnosing geostrophic velocity from sea surface height (SSH) is limited to about 70 km in the southern CCS. Seasonality in the CCS is much weaker than in WBC regions, although it could impose a modulation in the accuracy of geostrophic velocity estimated from SSH, with better accuracy in winter and spring.

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Land Processes and Inland Water #3: Rivers, Wetlands and Soil Moisture

The Yukon River in Alaska and the Great Ruaha River in Tanzania: Assessing River and Wetland Dynamics to Aid Ground-Based Monitoring Networks and Ecological Restoration Projects within Complex and Diverse River Basins.

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Satellite-based altimetric data sets can be utilized to monitor both water level variations and channel surface gradients for the largest river systems and wetland regions around the world. Here, we focus on the Yukon River in Alaska and the Great Ruaha River in Tanzania. Despite its extent and complexity, few US and Canadian gauges exist across the Yukon basin. This hampers modelling and basin dynamics efforts, particularly affecting flood predictions and fisheries analysis. There are also minimal ground-based observations of river flow and water storage within the Great Ruaha/Usangu wetland system despite increasing stress on water resources and the need to maintain ecological balance.

Historical, current, and future, conventional and enhanced, radar and lidar altimetric data sets offer spatially and temporally varying measurements, continuity, and cross-validation checks. Here, we look to the merits of combining results from multiple instrument platforms, and examine the advantages of the Delay-Doppler measurements from Sentinel-3A in terms of improved along-track spatial resolution. Overall instrument performances, particularly in terms of river reach acquisition, are summarized, together with a future look at providing operational river and wetland products to a wide range of end users and stakeholders via the G-REALM (lake-monitoring) system.

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Channel Storage Change: a New Remote Sensed Surface Water Measurement

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Here we present river channel storage change (CSC) measurements for 17 major world rivers from 2002-2016. We combined interpolated daily 1 km resolution Global River Radar Altimeter Time Series (GRRATS) river

surface elevation data with time varying widths derived from Landsat data, to generate channel storage measurements. CSC is a previously unmeasured component of the terrestrial water balance with global bearing on floodplains, ecology, and geochemistry. CSC calculations allow for studying remote regions where hydrological data is not easily accessible. CSC is well suited to determine the role of hydrologic and hydraulic controls in basins with strong seasonal cycles (freeze-up and break-up). The cumulative CSC anomaly can impart spatial details that point measurements cannot, highlighting floods and ice jams and allowing for comparisons of relative contributions from tributaries. With CSC, we may be able to determine critical hydrological and hydraulic controls on rapidly changing systems like Arctic rivers. Preliminary results for Arctic river systems have shown that CSC is responsive to climatic forcing in ways that river discharge is not. Results for the Yukon River show that from 2002 on, CSC has been shifting from a pattern consistent with early season snowmelt and late season lake runoff only, to show more mid-season peeks, which are associated with glacier runoff and rain. From 2002-2007, only one CSC season had more than 2 peaks. Every year thereafter, (2008 -2016) had at least three with an average of four. The first and last CSC peaks of the years are an average of 102 days apart over the 14 year time series. The maximum timespan was 149 days in 2004 and the minimum was 71 days in (2016). Four years had at least a standard deviation less than the mean amount of days between peaks. This could be indicative of intensification of the Yukon water cycle, and have serious implications for erosion, carbon cycling and river ecology

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Potential of the Radar Altimetry for Estimation of the River Input to the Arctic Ocean

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Since already ten years, the radar altimetry have been successfully used for estimation of water discharge of large rivers. The arctic rivers are the most challenging objects from methodological point of view as 1) they are covered by ice during the most part of the year and 2) significant part of the water flow passes after the snow melt during only several weeks. In the framework of the ESA ArcFlux project, aiming an estimation of the fresh water fluxes in the Arctic Ocean, a performance of the radar altimetry for precise estimation of the water flux for different types of the arctic rivers was studied. The test was performed for two large rivers: the Ob River (regular gentle flooding regime) and the Lena River (rapid and sharp spring and summer floods) and for one middle size river Pur (Western Siberia). We investigated different approaches to retrieve water level from different altimetric missions starting from 2002 (single-mission/single-track, single-mission/multi-tracks, multi-missions) and investigated two different methods of discharge estimation (stage-discharge rating curves and Manning solution). The results show very high potential for multi-mission and multi-tracks approaches. The Manning solution, which can be used for discharge estimation for ungauged rivers, also provides very good results. The accuracy of the annual water flow estimates for middle size river is of 17%, while for large rivers it is of 4-7%.

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Multi-Mission Satellite Remote Sensing for River Discharge Estimation: Recent Advances and Future Directions

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River discharge monitoring is of paramount importance for water supply management, hazard monitoring, urban planning and so on. For more than a century, river discharge has been indirectly measured in the river through observations of water level and flow velocity, but recently the number of worldwide gauging stations has decreased. The matter increases the interest to apply remote sensing data for hydrological purposes and the growing availability of different sensors, fosters the monitoring of different physical parameters of river, which can be representative of the discharge.

In particular, the recent advances in radar altimetry technology offer important information for the river water level monitoring and mainly the multi-mission products help to face with the limitations due to the spatial and temporal resolution of each sensor. If the altimetry is used in synergy with other satellite sensors, its potential benefits grows significantly, becoming an important instrument for the estimation and the forecast of the river discharge. Indeed, coupling the altimetry and the optical sensors allows to achieve information useful especially during flood events when cloud coverage hinder the river monitoring by optical sensors.

On this basis, this work attempts to provide an overview of the current research efforts on the estimation and forecasting of river discharge at gauged and ungauged sites by shedding light on advanced methodologies and the recent progresses in the merging procedure.

Moreover, the future directions of this research activity will be illustrated in terms of: 1) optimization of the integration/merging procedure by considering different sources of data, 2) full exploitation of the method for improving hydrological (floods, drought), climate and agricultural (insurance) applications, 3) optimization of the space-time resolution of satellite observations so that processes can be well identified by models.

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Soil Moisture from Satellite Radar Altimetry-from ERS-2 to Sentinel-3

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Measuring soil surface moisture using satellite radar altimetry is a comparatively new application. The technique reported here uses very detailed DRy EArth ModelS (DREAMS) [1], based on multi-mission recalculated and cross-calibrated altimeter backscatter fused with ground truth. At present there is a requirement that the surface be dry for at least one month of the year; thus current implementation is over desert and semi-arid terrain.

The objectives of this research are fourfold. Firstly, the development of enhanced DREAMs for use with Sentinel-3 data; secondly creation of long time-series from prior missions to put Sentinel-3 soil moisture results in context; thirdly, external validation of these time series and fourthly, as data accrue, to create soil moisture time series from Sentinel-3 data.

For the CryoSat-2 mission, both the DREAMS and the soil moisture derivation schema had to be re-engineered because the mission long repeat period precluded use of repeat arc analysis to identify remaining areas of model instability [2]. However, the unique dense spatial coverage of desert regions provided a comprehensive test dataset to challenge the augmented DREAMs over further desert areas. Initial research led to successful retrieval of soil moisture over the Tenere, Simpson and Kalahari deserts from CryoSat-2 and co-temporal Jason-2 data; the results were validated with the ESA Climate Change Initiative (CCI) dataset [3] and showed good agreement.

Model building is now complete for the Victoria and Gibson deserts in Australia, and the Arabian Desert. CryoSat-2 and Jason-2 soil moisture time-series have been created over these deserts. The new schema and DREAMs have now been used to generate soil moisture estimates from ERS-2 and Envisat backscatter to extend the time series; these have been cross-validated with CCI data [3] at its full spatial resolution. Example multi-mission time series and validation outcomes are presented from this major study.

Finally, an assessment of Sentinel-3 backscatter performance over the DREAMs is discussed; first soil surface moisture results from Sentinel-3 are shown, and evaluated in the context of prior missions.

1 Berry, P.A.M., Dowson, M., Smith, R.G., Benveniste, J., 2012; "Soil Moisture From Satellite Radar Altimetry (SMALT)", in Proceedings of the "20 Years of Progress in Radar Altimetry" Symposium, Venice, Italy, 24-29 September 2012, Benveniste, J. and Morrow, R., Eds., ESA Special Publication SP-710, 2012. http://dx.doi.org/10.5270/esa.sp-710.altimetry2012.

2 Berry, P.A.M. & Balmbra, R., 2016. Soil Surface Moisture from Cryosat2 and Sentinel-3 Satellite Radar Altimetry. Proc. 'Living Planet Symposium 2016', Prague, Czech Republic, 9–13 May 2016 (ESA SP-740, August 2016).

3 Dorigo, W.A., et al, 2017. ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. In Remote Sensing of Environment, 2017, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2017.07.001

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Altimetric Contributions to Gravity Field, Marine Geodesy, Bathymetry Modeling

KEYNOTE: Marine Gravity Field Mapping from Altimetry – Advancement with 2nd Generation Altimeters

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Until the launch of Cryosat in 2010 the only geodetic data available for deriving high resolution marine gravity fields were the 1985 Geosat GM and 1995 ERS-1 phases E and F. Geodesists therefore spent the better of 15 years improving these GEOSAT and ERS-1 data.

With the launch of the second generation altimeters CryoSat and SARAL/AltiKa and the completed geodetic missions from Jason-1 as part of the retirement orbit, a new era in satellite altimetry has been initiated.

Since 2010 the amount of geodetic mission altimetry has nearly four-doubled. At the same time the signal-to-noise ratio in these new satellite's range measurements is better than that of Geosat and ERS-1, and this is leading to huge improved resolution of marine gravity anomalies. Today the quality of altimetric marine gravity is on the order of 1.5 to 2 mGal depending on region. This surpasses what can be obtained from marine gravity in many regions of the world.

The quality of global high resolution marine gravity field will always be limited by the random noise level in the radar range measurement as well as the ground track spacing. Over the years geodesists have made significant advances in retracking algorithms, cutting range error nearly in half, and leading to improvements that have been a benefit to oceanography.

Cryosat-2 provides for the first time altimetry throughout the Arctic Ocean up to 88°N as well as delay-Doppler (SAR) altimeter in scattered regions aroumd the world where the multi-looked on-board processing can be used for improved range precision at even higher along track resolution than conventional satellite altimetry (LRM).

In the near future we are looking towards several new revolution in high resolution marine gravity field mapping. The first will be the completion of the 2-year Jason-2 End of Life geodetic mission which will decrese the groundtrack spacing from 8 km today to 4 km which will enable scientist to resolve further high resolution in the marine gravity field. The second will be the availability of ultrahigh resolution SWOT altimetry from year 2021.

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The Coastal Mean Dynamic Topography in Norway Observed by CryoSat-2 and GOCE

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The Norwegian Coastal Current (NCC) transports warm and relatively fresh water along the Norwegian coast and into the Barents Sea, with its origin in Baltic water entering Skagerrak. Along its way northward it is fed by additional freshwater discharge. The NCC is important for the regional marine ecosystem and contributes to the poleward transport of warm Atlantic Water, maintaining the relatively mild climate in northwest Europe.

Although satellite altimetry is a mature technique, globally observing the sea surface height with an accuracy of a few centimeters, numerous effects degrade the observations in the coastal zone. For example, the radar footprint is contaminated by land and bright targets, and the range and geophysical corrections become difficult to model. The rugged Norwegian coast presents a further challenge, and the NCC, at times only a few tens of kilometers wide, typically falls into a zone where conventional altimeters do not deliver reliable observations.

The European Space Agency's CryoSat-2 (CS2) satellite is the first to carry a SAR altimeter instead of the conventional pulse-limited system, resulting in higher range precision and along-track resolution. This allows for tracking finer structures of the sea surface and get closer to the coast. We use CS2 low resolution and SARIn observations along the Norwegian coast and determine a mean dynamic topography (MDT) that is validated using tide gauges. In turn, geostrophic surface currents are derived from both the CS2 MDT and the operational coastal numerical ocean model of the Norwegian Meteorological Institute, and compared. For the first time, the NCC is revealed by space-geodetic techniques, giving confidence in the new-generation SAR altimeters for coastal sea level recovery.

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Opportunities and Challenges of Satellite Altimeter Gravity over Lakes.

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The process of calculating satellite altimeter gravity over lakes, whilst largely the same as over open sea, has some particular features. In this study we calculated gravity over twenty of the world's largest lakes.

There are no significant tides over even large lakes, but there can be significant variation in water height between seasons and between years. These height variations are largely unpredictable and statistical cross-over levelling and micro-levelling techniques are used to generate a coherent network of tracks to produce a reliable lake height grid ready for conversion to gravity. Appropriate choice of reference height is important for edge control prior to gravity conversion. More positively, waves are generally small and the surface gives good radar reflections.

ERS-1 did not record useful data over lakes or inland seas and hence there are fewer geodetic satellite missions contributing to the satellite gravity calculation. CryoSat-2 and Jason-1 data give generally good coverage; Geosat data are also available and the coverage overall is good, although the irregular track spacing can leave some apparently substantial gaps in these smaller areas of water. CryoSat-2 operates mostly in LRM or SAR-In mode over lakes. Analysis of the SAR-In mode has been particularly useful due to the generally relatively calm surface of lakes, as well as allowing slightly enhanced coverage due to its ability to track the water surface some distance away from the track. Due to the high percentage of lake area that is close to the shoreline, particular care is taken in the editing stage to preserve lake surface height data as close to the shore as possible.

Lineaments extracted from the resulting gravity grids show good correlation with geological structures seen in lake seismic data and coherent gravity can be produced for lakes as small as Lake Edward (2,300 km2). Airborne gravity (GRAV-D) surveys in North America provide an opportunity for comparison over whole lakes, although the higher elevations of the airborne data sets make the comparison less direct.

A key attraction of lake satellite altimeter gravity is to complete the gravity coverage of continental areas and hence integrating the satellite data with adjacent onshore gravity is important. Direct integration of grid-only satellite gravity with land point gravity values can be achieved by a range of empirical adjustment processes such that the resulting grids maintain continuity of features and avoid sharp discrepancies. Equivalent source techniques have been tested to achieve more direct integration of the two data sets. One attraction is that satellite-derived lake-surface heights can be integrated directly with gravity observations without the need to consider the edges of the lake data set. Appropriate levels of smoothness can be achieved through choice of equivalent source spacing and depth as well as by direct constraints on curvature of the result. Lake satellite tracks provide good coverage over all large lakes, but gravity point coverage is often patchy. Thus, integration is challenging whatever approach is employed, but continuous gravity grids are of great value – especially in geological interpretation.

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Precise Orbit Determination

REAPER Re-Scoped: Updated Orbit Solutions for the Full ERS-1 and ERS-2 Mission Periods

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New orbit solutions for the ERS-1 and ERS-2 satellites are provided as an update to the solutions generated in the framework of the REAPER project (Reprocessing of Altimeter Products for ERS, funded by the European Space Agency-ESA). The new solutions are consistent with the GDR-E standards adopted for current altimeter satellites. In addition, the new solutions cover the full mission period for ERS-2, i.e. the period from June 2003 to July 2011 is taken into account as well. The latter results in ERS-1 and ERS-2 orbit solutions that cover, respectively, August 1991-July 1996 and May 1995-July 2011. The final orbit solutions are a combination of two orbit solutions by PosiTim UG (Germany) and Delft University of Technology (The Netherlands), using a combination of Satellite Laser Tracking (SLR) and altimeter crossover observations, augmented with Precise Range and Range-Rate Equipment (PRARE) tracking observations when available. The quality of the orbit solutions is assessed by comparing the individual orbit solutions with each other, orbit overlap analysis, fit of tracking and altimeter crossover observations, and sea level records.

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Reprocessing of TOPEX/Poseidon Precise Orbits in the CNES GDR-F Standards

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During 13 years, from its launch in 1992 to the end of 2005, the TOPEX/Poseidon (T/P) mission monitored the mean sea level with a precision of a few centimeters. The newer altimetry satellites allowed its measurement precision to be improved through cross-calibration and orbit reprocessing with more precise dynamical and correction models. This study presents the results of the first CNES reprocessing of the T/P orbits with the GDR-F standards using DORIS and SLR measurements.

This standard uses updated implementations of the ITRF2014 for the computation of the DORIS and SLR station coordinates (DPOD2014 and SLRF2014). In addition, the time variable gravity field model is updated with the measurement time series from GRACE, combined with a mascon model for the beginning of the mission (when GRACE was not yet launched). Finally, this standard uses new estimations for the geocenter motion with a new IERS linear mean pole. This study also explores the orbit improvements obtained by introducing SLR data while estimating a range bias for each SLR pass.

To assess the quality of this reprocessing, the orbits are compared to those from the NASA/Goddard Spaceflight Center, through the computation of crossover residuals and geographically correlated orbit differences.

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First Orbit Determination Results for Sentinel-3B

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Sentinel-3B, the twin satellite of Sentinel-3A, is planned to be launched in April 2018. During commissioning phase the radar altimeter satellite will fly in tandem (30 sec apart) with Sentinel-3A. This is mainly done for calibration and validation of the SAR altimeter instrument.

The commissioning phase of Sentinel-3B and thus the tandem flight with Sentinel-3A will also be used to do several tests with the GPS receivers on-board Sentinel-3B. Both GPS receivers will run in parallel with the main one in the same configuration as the main receiver on Sentinel-3A and with the redundant one in different configurations to test the GPS L2C capability.

First Sentinel-3B orbit results are presented from the Copernicus POD (Precise Orbit Determination) Service. Sentinel-3B is the sixth satellite being processed by the CPOD Service, which is part of the Copernicus PDGS of the Sentinel-1, -2, and -3 missions. The nominal orbit determination procedures (Near Real Time (NRT), Short Time Critical (STC), and Non-Time Critical (NTC)) for Sentinel-3B are set up in the same way as for Sentinel-3A. The accuracies are compared to the corresponding accuracies achieved for the twin satellite.

Comparisons to independent orbit solutions from CNES and from the Copernicus POD Quality Working Group are shown as well as validation based on SLR measurements and DORIS–derived orbits. Additionally, results of the specific investigations based on the different Sentinel-3B GPS receiver configurations are presented.

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Improved GNSS Phase Maps in Flight Modelling and Identification, Application on Jason-2 and Jason-3

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The OSTM/Jason-2 and Jason-3 missions are the altimetry reference missions dedicated to mapping ocean-surface topography. As such, the overall orbit accuracy is a prerequisite for the exploitation of their measurements. For this purpose, the two spacecraft carry onboard tracking instruments for precise orbit determination (POD), including a GPS receiver. The accuracy of the models used for measurement modelling is a source of systematic errors. Indeed, the actual location of the antenna phase center and its fluctuations with respect to the direction of the received signal need to be accurately known.

The current practice is to estimate the phase center offset (PCO) simultaneously in orbit with the other parameters (dynamic modelling, phase ambiguities). The phase center variations (PCV) are then obtained by residuals stacking, in an iterative process (orbit determination > residuals stacking map > orbit determination > ...). The drawback of this approach is that the PCV model may still absorb some low degree variations not correctly represented by the initial PCO adjusting, and in this case the PCO/PCV map is not correct. There are also observability issues: due to the PCV construction process, a globally unobservable parameter may be observed using the two-step iterative procedure.

Thus, a new PCO/PCV model construction method has been developed using Zernike polynomials. The initial model is a parametric model (11 parameters) adjusted simultaneously with the other orbit and measurement parameters. Depending on the attitude law, some components are clearly not observable. This model represents the low-frequency patterns. A correction is then determined from the in-flight residuals to retrieve the remaining high-frequency patterns which are well decoupled from the other model parameters. This method was applied to estimate the phase maps for the Jason-2 and Jason-3 GPS antennas. They were validated on reduced-dynamic GDR-F orbit solutions and compared to the pre-launch or in orbit phase maps provided by JPL. We finally analyze the post-fit GPS phase residuals, independent SLR residuals and induced orbit differences.

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Generating Precise and Homogeneous Orbits for ESA's Altimetry Missions: ERS-1, ERS-2, Envisat, Cryosat-2, and Sentinel-3A.

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Driven by the Copernicus and GGOS (Global Geodetic Observing System) initiatives the user community has a strong demand for high-quality altimetry products. In order to derive such high-quality altimetry products precise orbits for the altimetry satellites are needed. Satellite altimetry missions meanwhile span over more than 25 years, in which our understanding of the Earth has increased significantly. As also the models used for orbit determination have improved, the satellite orbits of the altimetry satellites are not available in a uniform reference system. Homogeneously determined orbits referring to the same global reference system are, however, needed to improve our understanding of the Earth system.

The Navigation Support Office at ESA/ESOC provides precise orbits for all of ESA's altimeter missions: ERS-1, ERS-2, Envisat, Cryosat-2 and Sentinel-3A. In 2008 (and again in 2018) ESA initiated the re-processing of the altimetry data of ERS-1, ERS-2 (REAPER), including the reprocessing of the orbit determination for these satellites. But also, the other altimetry satellites, as Cryosat-2, Envisat and Sentinel-3A, benefit from re-processing. The Navigation Support Office has with its NAPEOS software package the capability to process all three satellite geodetic tracking techniques (SLR, DORIS and GNSS). Therefore, we are in the unique position to do orbit determination by combining different types of data, and by using one single software system for different satellites, which matches the most recent improvements in orbit and observation modeling and IERS conventions. Thus, we are able to generate a homogeneous set of precise orbits referring to the same reference frame for the various altimetry missions. Furthermore, we are able to quickly re-process all solution allowing us to continuously upgrade the various solutions for all satellites.

This presentation focuses on the latest results from the re-processing efforts carried out by ESA/ESOC for the generation of precise and homogeneous orbits for ERS-1, ERS-2, Envisat, Cryosat-2, and Sentinel-3A. For ERS-1 and ERS-2 SLR data are combined with altimeter data whereas for Envisat and Cryosat-2 DORIS and SLR data are combined, and for Sentinel-3A GPS observations are used in addition to DORIS and SLR. We will present the orbit determination results and evaluate the orbit accuracy by comparing our orbits with external orbits generated by other analysis centers and will highlight some of the improvements obtained from our most recent upgrades.

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Latest Results from the Geomed2 Project: Geoid and the DOT in the Mediterranean Area

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The main aim of the Geomed2 project was the estimation of the best possible geoid approximation, given the available marine gravity data, for the wider Mediterranean area, i.e. in the area bounded between 30 < < 48 -10 < < 40, on a 2’ 2’ geographical grid.

For the geoid estimation, all available shipborne gravity data have been collected, edited, homogenized and used to derive the most homogeneous possible dataset in order to devise a gravimetric only geoid model. In that respect, special attention has been paid to the data debiasing, where both area-wise and track-wise methods have been employed. The geoid estimation was based on the well-known remove-compute-restore method, employing different approaches for the actual geoid modeling. The latter refer to the use of least squares collocation, Fast-collocation, 1dFFT and 2dFFT employing the original Wong&Gore modified Stokes kernel, and finally the KTH. The available gravity data have been gridded on a regular 2' 2' grid in the computation area employing ordinary krigging, serving both as input to the geoid estimation methodologies and as a project deliverable to be disseminated as a new approximation of the gravity field over the Mediterranean. When required, the low frequency components of the gravity field have been modeled using EIGEN-6c4 to d/o 1000 and different methods for RTC reduction have been tested.

The estimated geoids have then been compared with altimeter data to obtain different estimates of the Mean Dynamic Topography (MDT), which in turn allowed the definition of the currents pattern in the Mediterranean Sea. We present the advantages and pitfalls of each processing step, discussing the possible sources of noise and errors, while finally devising a final optimal estimate to be used for geodetic and oceanographic applications.

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Jason-3 and Sentinel-3A GPS Processing Using Zero-Difference Integer Ambiguity Fixing

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In the past, it was proven that for Jason-1 GNSS data, GPS ambiguities could be fixed, however, that was not possible on OSTM/Jason-2 because the phase measurements were not constructed with integer-valued ambiguities due to a low signal-to-noise ratio (half-cycle ambiguities only). Thus the current CNES GPS-based solutions on Jason-2 use floating ambiguities. This has been reconducted for the beginning of the missions of Jason-3 and Sentinel-3A . For HY-2A, even if the measurements have full cycle ambiguities, an operational solution with ambiguity fixing has not yet been developed, as it was not necessary to achieve the radial orbit accuracy requirement.

However, on Jason-3, the receiver behaviour is excellent, and an ambiguity fixing solution has been developed at CNES. This is a zero-difference ambiguity approach, using specific biases and phase clocks provided by the CNES/CLS IGS analysis center (grg solution).

These new orbits lead to significant improvements in the radial performance (the high-elevation SLR residuals on the core network change from 10 mm to 7 mm rms between floating and fixed solutions).

For Sentinel-3A, a recent evolution in the telemetry ground processing now allows phase measurements with integer ambiguities. A similar solution as for Jason-3 is currently under development.

This presentation will summarize the different steps of this processing, and some specific dynamic or measurement characteristics which were observed (biases, systematic errors).

A comparison between the orbits obtained in the current solutions and the new solutions will also be presented

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The Geomed2 Combined Geoid Model

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The GEOMED 2 project computed a high-accuracy and resolution marine geoid model based on the availability of improved models for gravity, thanks to GRACE and GOCE in particular, for land topography and bathymetry, and the compilation of a cleaned-up and de-biased gravity database of the Mediterranean area based on BGI and SHOM data. Land and marine gravity data, the latest combined GOCE/GRACE based Global Geopotential Models and a combination of MISTRALS, EMODnet and SRTM/bathymetry terrain models were used in the gravimetric geoid computation. Computation of a gravimetric marine geoid of the Mediterranean is challenging due to:

- The poor coverage of the marine gravity data for certain areas;
- The inhomogeneous quality of the marine gravity data (bias, precision);
- The data reduction is not as efficient as achieved over land.

Marine gravity data is not available for large parts of the Mediterranean and consequently the gravimetric geoid solution is significantly less accurate there. Gravity inferred from altimetry data, or a mean sea surface corrected for mean dynamic topography (i.e., an 'oceanographic' geoid model), can be used to fill the gaps. However, ocean dynamic signal may contaminate the derived gravity or geoid, which is why a pure gravimetric solution is preferred in an ideal world.

The effect on the geoid solution of using several altimeter-based datasets, such as DTU10, DTU15 and UCSD V24 gravity, using simple gap filling, weighted combinations with the gravimetric data, and combination through collocation, will be evaluated and quantified. The combined models are compared with the gravimetric geoid solution as well as with the oceanographic geoid. The (local) errors and increased uncertainty due to the data gaps, and the subsequent effect on the ocean mean dynamic topography and geostrophic currents, can be estimated via the results of all comparisons. All models are equally compared to drifter-inferred current velocities, which constitutes an independent quality evaluation. This type of evaluation leads to a very detailed quality assessment of the models, notably as a function of spatial scale.

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Orbit Validation of Sentinel-3 Mission

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Sentinel-3A is in orbit since two years now and the precise orbit determination (POD) is well established. The official orbit solutions from CNES and the Copernicus POD Service as well as other orbit solutions from several institutes, in particular from the members of the Copernicus POD QWG (Quality Working Group), are available. The orbit solutions are derived from different software packages, are based on different models, arc lengths and parametrizations, and are computed with different observables. Some solutions are based on GPS observations only, some on DORIS observations only, and others are combined solutions. SLR measurements are mainly used for validation but might also be used in a combined orbit determination.

Correct knowledge of the antenna and reflector offsets is fundamental to guarantee the required radial orbit accuracy of 2-3 cm for the analysis of the radar altimeter measurements. The three observation techniques available on Sentinel-3A offer the opportunity to compare and validate the offsets of the SLR reflector and the GPS and DORIS antennas against each other. Offset estimates are available from different groups and from different approaches. Validation of these offsets is done based on the analysis of the manifold orbit solutions using original and updated coordinates.

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Precise Orbit Determination of the Sentinel Satellites with Gipsy-Oasis

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The Sentinel family of earth-observation satellites, part of the joint EC-ESA Copernicus programme, have been launched since 2014 and currently 7 satellites are in orbit. Besides the official orbit solutions from CNES and the Copernicus Precise Orbit Determination (POD) service, orbit (validation) solutions are also generated by the members of the Copernicus QWG (Quality Working Group). All these solutions are derived using different scientific software packages. TU Delft already has a long-established track record in POD using e.g. the GEODYN (NASA) and GHOST (DLR) software. Recently also JPL's legacy GIPSY-OASIS software has been set up for analyzing the Sentinel GPS data.

The GIPSY-OASIS software has been successfully used by JPL for POD of the Jason 1, 2 and 3 satellites and TUDelft is currently using it for POD of the Sentinel 1, 2 and 3 satellite pairs. GIPSY provides the user with a variety of models and parameterization options, including spacecraft manoeuvre, data gap handling and carrier phase ambiguity resolution. First results for Sentinel-3A indicate, based on both internal and external (satellite laser ranging (SLR)) comparisons, that a 3D root-mean-square (RMS) accuracy of 8-10 mm is achievable. Additional altimeter crossover analyses will be performed for Sentinel-3A and possibly also with 3B after it has entered its operational service. Furthermore, the effect of different force models, data gaps, manoeuvre handling and ambiguity resolution will be investigated.

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25-Year Altimetric Record #1: Building the Climate Record: Accuracy and Precision over 25 Years of Altimetry Data

REVIEW: Evolution of LRM and SAR Altimeter Ocean Data Processing towards Improved Performances

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With the advent of the satellite radar altimetry in the early 1990s, allowing continuous monitoring of key ocean parameters (the sea level, waves and winds), climate and operational oceanography applications have emerged, and are still evolving thanks to the development of innovative instrumentation (e.g. Ka-band radar altimetry, SAR-mode altimetry, altimetry interferometry technique) and data processing. Improvement is needed to meet new operational oceanography requirements that are relevant, for example, to the study of mesoscale/submesoscale variations in deep ocean and other phenomena more closely.

A major advance in altimeter design has been made with the delay/Doppler altimeter. Advantages brought by this radar mode to retrieve geophysical ocean parameters with much higher resolution and precision than conventional pulse-limited altimeters are now well acknowledged. Cryosat-2 and Sentinel-3A are the first satellites operating with a synthetic aperture radar (SAR) altimeter capability, demonstrating improved ocean measuring performance, with a potential however that is far from having been exhausted. In recent years many active researches have been carried out to gain a better understanding of the limitations of SAR-mode data as processed by the ground segments. In the meantime some initiatives have been undertaken to better exploit the high resolution information in SAR altimetry observations [Egido & Smith, 2017], as well as to remove swells sensitivity thanks to an alternative stacking approach [Boy et al, 2017]. All these promising works have paved the way for the development of new level-1 SAR altimetry processing that would bring meaningful improvements in marine operational processing.

In parallel, huge efforts have been made to improve level-2 retracking processing, with the objective to reduce the estimation noise, which is a limiting factor for the detection of short wavelengths in the altimeter SLA spectrum. Among significant headway in the area, Thibaut et al. [2017] have developed a new retracker model and a Nelder Mead optimization method with an exact likelihood criterion which offer dramatic improvements in the estimation performances over ocean, and which at the same time allow a continuous processing of open ocean and sea ice surfaces. In conventional altimetry, the problem is more complex and in fact twofold. In addition to the noise issue, standard nadir-pointing radar altimeters exhibit short-wavelength correlated errors in the SLA spectrum that prevent observation of small scale features (ranging from 30 to 100 km). Some LRM ocean retracking strategies address these two issues [Sandwell & Smith, 2005].

This paper is a review of some of the most significant and recent advances in nadir altimetry data processing studies, aiming at improving the current LRM and SAR-mode data ground processing to further stimulate the generation of higher level quality data for the upcoming Sentinel-3 C/D and Sentinel-6 missions, while addressing the evolving needs of the end-users.

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Toward an Overview of CryoSat Data Quality over the Ice and the Ocean

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Over the past decades, satellite radar altimetry has shown its ability to revolutionise our understanding of the ocean and climate. Previously, these advances were largely limited to ice-free regions, neglecting large portions of the Polar Regions. Launched in 2010, the European Space Agency's (ESA) polar-orbiting CryoSat satellite was the first SAR/SARin altimeter concept specifically designed to measure changes in the thickness of the sea ice and the elevation of the ice sheets and mountain glaciers. Going beyond its ice-monitoring objective, CryoSat has also demonstrated to be a valuable source of observations for the oceanographic community by measuring high-resolution geophysical parameters from the open-ocean to the coast. Consequently, thanks to fruitful collaborations with partner agencies (CNES, NOAA), ESA has developed and implemented its own CryoSat Ocean Processor, to operationally generate new products specifically designed for oceanographers. The CryoSat Ice and Ocean processors operate now independently and follow two distinct processing baselines. To enable their full scientific and operational exploitation, the generated products continuously evolve and need to be quality-controlled and thoroughly validated via science-oriented diagnostics based on multi-platform in situ data, models and other satellite missions. This paper provides a review of the CryoSat data quality, covering all Cal/Val activities performed by ESA and its partners over the ice and ocean surfaces. Also discussed are the forthcoming evolutions of the CryoSat data products and improvements anticipated in the next processing Baselines.

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DUACS Multi-Mission Sea Level Products: Continuous Improvements for the Past 20 Years

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In 1997 the first homogeneous and user friendly Sea Level data set based on TP and ERS1 & 2 missions were released to the scientific community: from this date, it was not necessary anymore to be an altimetry expert to use sea level time series. This was the beginning of DUACS (Data Unification and Altimeter Combination System), a long and sucessful story. All the altimeter missions from all the Space Agencies have been successively integrated in the system as soon as the data have been made available and assessed: GFO, Jason-1, Envisat, Jason-2, Cryosat-2, HY2A, Altika, Jason-3 and Sentinel3A.

The DUACS system produces, as part of the CNES/SALP project, and the Copernicus Marine Environment and Monitoring Service, high quality multi-mission altimetry Sea Level products for oceanographic applications, climate forecasting centers, geophysic and biology communities... These products consist in directly usable and easy to manipulate Level 3 (along-track cross-calibrated SLA) and Level 4 products (multiple sensors merged as maps or time series) and are available in global and regional version (Mediterranean Sea, Arctic, European Shelves …). As the knowledge of altimetry processing has been refined and as the oceanography needs has evolved the system has continuously been upgraded to increase the production frequency and to improve the resolution of the products and their accuracy. Full reprocessing have been regularly performed since 20 years to homogenise the time series. In 2018, a 25 year of altimetry, representing a total of about 70 years of cumulated data, will be released in the DUACS DT-2018 version. Beside the operational products, the development of the new generation of DUACS product has started. Using the global Synthetic Aperture Radar mode (SARM) coverage of Sentinel-3A, soon completed by Sentinel-3B, and optimizing the LRM altimeter processing (retracking, editing, ...) will allow us to fully exploit the fine-scale content of the altimetric missions and propose Level3 5Hz products. Level-4 products will also improve by combining these new Level-3 products and new mapping methodology.

The objective of this presentation is to make a synthesis of the major improvements of DUACS multi-mission products throughout the past 20 years and express the challenge of the coming years.

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Lessons Learned from 25 years of Cross Calibration of the Altimetry Missions Over Ocean

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Since the very first years of altimetry in the nineties, several altimetry missions have been flying together, resulting in a constellation varying from 2 to 6 altimeters sampling the oceans. The success of the altimetry time series lies, among others, in the validation activities carried out to assess the data product quality and mission performance.

Thanks to the support of the CNES SALP project and more recently from ESA MPC project, CLS CalVal team has been responsible for the mission performance assessment of several altimetry missions since 25 years.

Different types of metrics are traditionally used to assess data quality. The validation results take benefit in using different approaches: metrics based on single mission, comparisons with external sources such as in-situ data and models but also cross calibrations between the different altimetry missions. These different metrics aim at assessing the data performance at different time and spatial scales. The product quality has continuously improved thanks to the progress done on the various components used to derive sea surface topography but also on wind and waves parameters. As data quality is improving, validation activity become more and more demanding, requiring robust methods and metrics to measure the performance on the one hand and detect errors on the other hand.

This paper aims at highlighting all the achievements done in the past 25 years on mission performance assessment, thanks to cross calibration between the different altimetry missions. A focus will be done on the past 5 years during which several new types of mission have emerged. In addition to the historical missions on TOPEX and ENVISAT ground tracks, there are more missions with different characteristics or orbits: SARAL/AltiKa which is the first altimetry mission to operate in Ka-band and offers and improved noise and resolution, Sentinel-3A STM which is the first altimetry mission with Delay Doppler processing deployed at global scale, also offering enhanced measurement of the smaller oceanic scales. An important piece in the validation approach is the mission commissioning based on tandem phases that has been successfully repeated with Jason series of satellites and will be reused by the Sentinel-3 first missions. We will also discuss how these specific configurations improve our capability in detecting errors and insure accurate altimetry data records.

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In Situ Calibration and Validation of Satellite Altimetry: A Review of 25 Years of Ongoing Monitoring

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Sustained in situ calibration and validation undertaken at dedicated sites remains an integral component of satellite altimeter mission design. Fundamental to the success of the Jason-series reference missions, the dedicated sites are carefully instrumented to yield independent in situ estimates of sea surface height, directly comparable to those observed from the altimeter system. Ongoing cycle-by-cycle comparison provides an important system-wide performance assessment under a range of different oceanographic conditions. The stringent accuracy specifications dictate that in situ calibration and validation is a highly multidisciplinary problem in and of itself, requiring ongoing advances in terrestrial, oceanographic, and space-based observational techniques to keep pace with advancing altimeter technology.

Operated by mission agencies and international collaborators, the ongoing dedicated facilities located at Harvest (USA), Corsica (France), Bass Strait (Australia) and Gavdos (Greece) have their heritage in the early pioneering Bermuda experiments for the GEOS-3 (1976) and Seasat (1978) altimeter missions. Further validation experiments followed at the Acqua Alta oceanographic tower offshore from Venice for the ERS-1 mission (1991), prior to the launch of TOPEX/Poseidon mission (1992) heralding the beginning of the precision era of satellite altimetry. At this time, what was to become the Jason-series orbit was specifically designed to overfly dedicated in situ facilities at Harvest platform off the Californian coast and on the islands of Lampedusa and Lampione between Sicily and Tunisia. A third site was commissioned in Bass Strait, Australia, yielding important validation information from the Southern Hemisphere.

The in situ facilities at Harvest and Bass Strait remain in operation today having provided over 25 years of continuous monitoring. The facility at Lampoine was moved to Cape Senetosa (Corsica) in 1998, and an additional permanent facility was commissioned at Gavdos (Greece) in 2001. These four sites have continued to evolve to provide absolute calibration and validation information for the Jason-series missions, and more recently, other altimeters in the constellation including SARAL/AltiKa and Sentinel-3A.

Here we review 25 years of ongoing monitoring from the dedicated sites. We detail site specific differences in local conditions and elucidate subtle differences in methodology used to derive local in situ sea surface height. The error budget from each site is reviewed to assess site specific advantages and disadvantages, as well as to further describe the inherent challenges of in situ determination of sea surface height at the accuracy specifications required. We discuss the successes and ongoing challenges associated with the calibration and validation of satellite altimetry, and conclude with a perspective of requirements from future advanced altimeter missions.

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Synergy Between Altimetry, other Data and Models in Support of Operational Oceanography #1

Improved Global Surface Currents from the Merging of Altimetry and Sea Surface Temperature Data

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Through a joint effort between the Italian National Research Center (ISAC-CNR), the French National Space Agency (CNES) and the European Space Agency (ESA), a multiyear dataset of surface velocities have been calculated over the global ocean by combining altimeter derived geostrophic velocities and Sea Surface Temperature (SST) data. The method is based on the inversion for the velocity of the heat conservation equation using the altimeter velocities as background. By accurately prescribing the error both on the background velocities and on the forcing term (heat fluxes), the surface velocities are successfully improved in areas characterized by strong SST gradients and remain unchanged in low SST gradient regions, where by construction no additional information may be brought by the SST field. This allows us to provide for the first time a global field of surface velocities from the merging of altimetry and SST. Both the spatial and temporal resolution of the altimeter derived velocities is enhanced by the SST information. Validation is performed through comparison to in-situ drifting buoy velocities. Major improvements (10-20% globally, up to 40% locally) are obtained on the meridian component of the velocity and in the equatorial band. Due to the large uncertainty on the heat fluxes and the spatio-temporal resolution of the input datasets, the high frequency ageostrophic components of the circulation is hardly resolved by the method and, outside the equatorial band, improvements are mainly on the geostrophic component. It is shown that the level of accuracy obtained by combining altimeter velocities based on a two satellite configuration and microwave SST data is equivalent or higher to the one from a four altimeter constellation in western boundary currents. This opens the perspective for a systematic use of the method to improve the altimeter derived surface velocities over the 1993-2001 period, for which only 2 altimeters have been flying simultaneously. Finally, over the recent years, the use of higher resolution microwave + infrared SST products leads to further enhancement of the accuracy of the altimeter velocities on both the zonal and the meridional component in strong SST gradients areas. This dataset is planned to be distributed in the near future through the CMEMS (Copernicus Marine and Environment Monitoring Services) MULTI OSERVATION (MULTIOBS) Thematic Assembly Center (TAC).

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Implementation of a Balance Operator in a Multi-Scale Data Assimilation System for Operational Forecasting

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The advent of global, high-resolution surface observations, like those to be provided by the Surface Water Ocean Topography (SWOT) mission, presents a challenge for current operational data assimilation procedures that are optimized for the coarse observational types presently available. Multi-scale analysis procedures have shown promise for properly assimilating both coarse and high-resolution observation types. Additionally, the implementation of balance operators provides an efficient route to construct adequate cross-correlation in the background error covariance matrices. The presented efforts revolve around fusing these two techniques together by implementing scale dependent balance operators in a multi-scale analysis procedure. We demonstrate results from such a system by producing an Observing System Simulation Experiment (OSSE) utilizing the Navy Coastal Ocean Model (NCOM) regional, operational forecasting system. Scale dependent balance operators were

derived and used to build appropriate background covariances for both the mesoscale and submesoscale regimes. In the multi-scale system, coarse profile and nadir altimetry observations can be assimilated alongside high-resolution SWOT surface observations without using a single set of assumptions for covariances and decorrelation length scales. OSSE results demonstrate the utility of this new approach by comparing forecast errors from the single scale and multi-scale assimilation procedures. Additionally, wavenumber spectra allows the quantification of the length scales constrained when utilizing the multi-scale approach instead of the single scale procedure. We find that the high resolution SWOT data are not properly leveraged in the simple single-scale approach and that the multi-scale solution is required to constrain wavelengths approaching the balanced submesoscale regime.

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Mapping Ocean Mesoscales with a Combined Doppler Scatterometer and Altimeters Constellation

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New concepts of spaceborne Doppler scatterometers to measure Ocean surface currens are emerging. In the context of an altimetry constellation observing the large scales (above 200km wavelength) of geostrophic currents, it is worth exploring the potential synergy with observations of the full surface current. This later includes geostrophic motions, but also Ekman, inertial oscillations, tidal (barotropic and baroclinic) surface currents and other ageostrophic processes.

Observing the sum of these components has an obvious added value to the single geostrophic component presently observed. In this study, we propose to quantify the contribution of the two observing systems combined to map the mesoscale (100km,10days) circulation.

Observing System Simulation Experiments (OSSEs) are conducted from very high resolution simulations resolving all components of the surface currents and topography. A multivariate optimal interpolation scheme is used to combine along-track topography with radial velocity synthetic observations unevenly distributed in time and space, following the sampling of the SKIM design (Ardhuin et al., 2017). Prescribing accurate covariances for both topography and currents, accounting for all components and their best linear dependences (cross current/topography terms) is the challenging point for exploiting the synergy. In a few key regional configurations (western boundary current, low-latitudes, eastern basins, …) we will quantify the mesoscale reconstruction with each system separately and with their combination, through metrics of residual errors and effective resolution of the signal.

The results shown in this simple linear analysis context are promising, offering perspectives to further exploit the synergy between surface currents and altimetry in more sophisticated analyzes including assimilative numerical models.

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Estimating of Any Altimeter Mean Seal Level (MSL) Drifts between 1993 and 2017 by Comparison with Tide-Gauges Measurements

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The global mean level of the oceans is one of the most important indicators of climate change. It incorporates the reactions from several different components of the climate system. Precise monitoring of changes in the mean level of the oceans, particularly through the use of altimetry satellites, is vitally important, for understanding not just the climate but also the socioeconomic consequences of any rise in sea level.

With the satellite altimetry missions, the AVISO Mean Sea Level (MSL) indicator has been calculated on a continual basis since January 1993: https://www.aviso.altimetry.fr/msl. 'Verification' phases, during which the satellites follow each other in close succession (TOPEX/Poseidon--Jason-1, then Jason-1--Jason-2 and Jason-2-Jason-3), help link up these different missions by precisely determining any bias between them. Other missions (SARAL/Altika, Envisat, ERS-1 and ERS-2, Cryosat-2, Sentinel-3a) are also used, after being adjusted on these reference missions, in order to compute Mean Sea Level at high latitudes (higher than 66°N and S), and also to improve spatial resolution by combining all these missions together.

The objective of this study is to estimate any altimeter Mean Seal Level (MSL) drifts between 1993 and 2017 by comparison with tide-gauges measurements. Two tide gauges networks are used : GLOSS/CLIVAR and PSMSL. The different source of errors impacting such comparisons are described and modeled in order to estimate the altimeter GMSL drift uncertainty for any altimeter periods between 1993 and 2017 included, within different confidence interval. This study is performed for the global MSL indicator based on reference missions (TOPEX-Poseidon, Jason-1, jason-2 and Jason-3), but also for all the complementary missions (ERS-1, ERS-2, Envisat, Geosat Follow-on, SARAL/Altika, Cryosat-2, HY-2A and Sentinel-3a). We present the great interest of theses analyses for MSL studies, focusing on TOPEX-A GMSL period where a significant drift of ~1.5 mm/yr between 1993 and February 1999 has been detected.

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Impact of Altimetry Observations in the Real Time Ocean Monitoring Systems: GODAE OceanView Observing System Evaluation Studies

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Ocean analysis and forecasts produced in real time by operational centers serve a wide range of applications, from marine safety to seasonal forecasts. Some of those centers are involved in GODAE OceanView, which provides a forum for national forecasting centers to communicate and exchange knowledge and expertise. The quality of the analysis and forecasts highly relies on the availability and quality of the in situ and satellite observations. Altimetry data are key observations for those systems as they provide integrated information over the water column, with a regular and global coverage.

The GODAE OceanView Observing System Evaluation (OSEval) task team focuses on observation impact assessment and observing system design. Impact experiments allow a better understanding of the role of the altimetry observations in constraining the model forecast and give insight on the data assimilation efficiency to ensure the best use of those observations. We will show the benefit of assimilating multi – satellite altimeter data sets nowadays but also the impact of the Mean Reference Surface and complementarity with the in situ networks. Use of a multi system approach ensures the robustness of the conclusions.

As the observation accuracy and resolution improve, the ocean models tend to increase their spatial resolution and complexity to resolve more scales and physical process (e.g., submesoscale phenomena, tides,...). The future constellation which will include wide swath altimeter will open a new era and several GODAE centers are adapting their system to ingest such data and evaluate their ability to constrain much smaller scales with a better accuracy than the actual constellation. Strong benefits are expected for downstream applications.

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Advances in our Understanding of Coastal Processes #1

From the Open Ocean to the Coast and Back with ALES: Bypassing Waveform Tail Artefacts to Observe the Coastal Sea Level Variability

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The Adaptive Leading Edge Subwaveform (ALES) fitting algorithm (retracker) was designed to maximise the amount of good sea level retrievals in the coastal zone without compromising the precision of open ocean data. It builds on previous attempts to exclude part of the returned radar signal to avoid signal perturbations due to land and calm water in the satellite footprint. Its rationale is the adaptation of the width of the fitting window for each received signal, depending on a first estimation of the wave height, which excludes part of the tail of the waveform while aiming at maintaining a good precision of the retrieved sea level.

With ALES, a coastal-dedicated retracker has been used for the first time to observe coastal sea level variability at subregional and seasonal scales. In the North Sea, ALES data combined with tide gauges helped detect the effect of a bathymetry slope on the annual cycle of the sea level. In the region of the Indonesian Throughflow, ALES data cross-calibrated with data from Cryosat-2 have been used to detect the area of influence of the semiannual Kelvin waves generated in the Indian Ocean at the monsoon transitions, the coastal sea level rise in the years 2002–2010 and the effect of the strong La Niña event of 2010.

ALES has improved the quality and quantity of altimetry data in the coastal zone, but it can also be used with confidence in the open ocean. Spectral analysis shows that ALES data improve the description of the sea surface height anomalies for wavelengths longer than 10 km, by improving the signal-to-noise ratio with respect to the other currently available retrackers.

ALES continues to evolve in both its design and its applications. A new version, called ALES+, has been coded to successfully recover measurement from the leads among the sea-ice covered region. Retrieving more and better SSH by specialised retracking data also yields improvements in other observables: studies are in progress to adapt the sea state bias correction to the ALES algorithm and are enlightening the relationship between this correction and the errors due to retracking. The significant wave height from ALES was used to observe waves during storm surges and describe the wave field up to the coastal zone. Harmonic analysis of ALES data are being used to detect residual tidal variability in the sea level anomalies and correct existing tide models.

Today, more than 15 years of ALES-processed altimetry data are freely distributed in a user-friendly format in the global ocean, providing sea level data that oceanographers can use without previous knowledge of retracking techniques. In the framework of the ESA Sea Level Climate Change Initiative, an enhanced post-processing of data is foreseen in order to join ALES progresses with other efforts dedicated to error estimation and improved geophysical corrections in coastal altimetry. The ALES experience shows that research in coastal altimetry is not only expanding the frontiers of our discipline, but also improving the knowledge in domains that we have been observing for the last 25 years

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Sentinel-3 SAR Altimetry over Coastal and Open Ocean: Assessment of Improved Retrieval Methods from the ESA SCOOP Project

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The European Sentinel-3 satellite, launched by ESA in February 2016 as a part of the Copernicus programme, is the second satellite to operate a SAR mode altimeter and is about to be followed by Sentinel-3B due for launch in spring 2018. The Sentinel 3 Synthetic Aperture Radar Altimeter (SRAL) is based on the heritage from CryoSat-2, but this time complemented by a Microwave Radiometer (MWR) to provide a wet troposphere correction, and operating at Ku and C-Bands to provide an accurate along-track ionospheric correction.

SRAL is operated in SAR mode over the whole ocean and promises increased performance w.r.t. conventional altimetry. SCOOP (SAR Altimetry Coastal & Open Ocean Performance) is a project funded under the ESA SEOM (Scientific Exploitation of Operational Missions) Programme Element, started in September 2015, to characterise the expected performance of Sentinel-3 SRAL SAR mode altimeter products, in the coastal zone and open ocean, and then to develop and evaluate enhancements to the baseline processing scheme in terms of improvements to ocean measurements. Another objective is to develop and evaluate an improved Wet Troposphere correction for Sentinel-3, based on the measurements from the on-board MWR, further enhanced mostly in the coastal and polar regions using third party data, and provide recommendations for use.

In this presentation we present results from the SCOOP project that demonstrate the excellent performance of SRAL in terms of measurement precision, and we illustrate the development and testing of new processing approaches designed specifically to improve performance close to the coast.

The SCOOP test data sets and relevant documentation are available to external researchers on application to the project team. At the end of the project recommendations for further developments and implementations will be provided through a scientific roadmap.

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SAMOSA++: A New Coastal SAR Altimetry Retracker and Its Application in German Bight and West Baltic Sea

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Unlike previous altimetric missions, the CryoSat-2 altimeter (SIRAL) features a novel Synthetic Aperture Radar (SAR) mode that promises higher resolution and more accurate altimeter-derived parameters in the coastal zone, thanks to the reduced along-track footprint.

Exploiting the CryoSat-2 SAR data in the recent years, many researchers have already proved that the performance of SAR altimetry with specific coastal retrackers is superior than collocated Pseudo-Low Resolution Mode (PLRM) coastal altimetry but they also pointed out that residual errors due to land contamination are still present in the very proximity of the land (0-3 km).

The objective of this work is to move on from this context and attempt to provide even better results exploiting some extra information provided by SAR altimeter as the Range Integrated Power (RIP).

Indeed, one of the novel data products of a SAR altimeter is the L1B-S or Stack product. This is a collection of all the Doppler beams steered to a fixed ground cell location.

From this new product, it is relatively straightforward to build a new waveform by a simple integration of the Doppler Beams in the range direction. This new waveform is referred to as the RIP. It characterises the backscattering nature of the ground cell where all the Doppler beams are steered to.

In this new retracker, that we coined SAMOSA++, the RIP, as computed from the L1B-S data, will be converted into a surface backscattering law and directly fed in the SAMOSA model as part of the model formulation. In this way, the SAMOSA model will be automatically able to cope with the different return waveform shape from different surface types: either diffusive or specular.

The mean square slope computed from the RIP will be estimated and it will represent a new output of the retracker. Its geophysical significance will be investigated.

The performance of the new retracker will be cross-compared against the SAR mode SAMOSA+ retracker [1], the TALES and SINC2 PLRM retracker [2] in the coastal zone and open ocean.

The region of interest to perform the validation is the German Bight and West Baltic Sea (being a very challenging area for radar altimetry due to its complex coastal morphology and its high tide dynamics and well furnished with in situ data), while the time of interest is the complete mission duration (7 years).

University of Porto will provide the GPD+ solution along the CryoSat-2 tracks [3].

Furthermore, the results of the SAMOSA++ retracker will be cross-compared versus the network of tide gauges and buoys in the German Bight managed by BfG (German Federal Institute of Hydrology) and WSV (German Waterway and Shipping Administration) and versus the output of the "Bundesamt für Seeschiffahrt und hydrographie" (BSH) regional circulation model and the wave forecast system of the "Deutscher Wetterdienst" (the DWD wave model).

Our goal is to assess the capacity of SAMOSA++ SAR mode retracker to bring the altimetric measurements even closer to the coast than with SAMOSA+ and with higher level of accuracy.

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Validation of Improved Significant Wave Heights from the Brown-Peaky Rretracker around East Coast of Australia

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Although satellite altimetry has been used to measure the significant wave height (SWH) over 25 years, extending the high quality SWHs to the coastal region still faces the challenge due to data contamination caused by land and low sea state within the altimeter footprint. In this paper, 3-year Jason-1 waveforms are reprocessed by a new Brown-peaky (BP) retracker to estimate SWHs. In addition, the Jason-1 SWHs from the Maximum likelihood Estimation 4-parameter (MLE4) retracker in the Sensor Geophysical Data Record (SGDR) product are adopted for comparison. We first analyse the data quality of 20 Hz SWHs and generate 1 Hz SWHs from the 20 Hz SWHs. These 1 Hz SWHs are then validated against SWHs from waverider buoys along the east coast of Australia.

The analysis of 20 Hz SWH data shows that, both BP and SGDR MLE4 derived SWHs have the standard deviation (STD) of ~0.5 m and similar number of valid 20Hz measurements within 1 Hz block. The quality of SGDR MLE4 SWHs drops as STDs increase to 3 m within distance 12 km to the coast. The quality of BP dataset, in contrast, remains without obvious change between 6 and 12 km offshore, though it drops within distance 6 km to the shore with STDs up to ~1 m. It also show that BP can retrieve more valid 20 Hz SWHs than the SGDR MLE4 for distance <8 km to the coast in the study area.

The validation of 1Hz SWHs is performed by calculating the along track point-wise bias, STD and correlation coefficient between altimetry and waverider-buoy SWHs. The results show that within 30 km off the coast the BP dataset has better agreement to buoy wave heights than that from SGDR MLE4 in terms of BP's smaller absolute bias, lower STD and higher correlation coefficient. It also shows the absolute bias increases with increasing distance from the coastline, which is relevant to width of continental shelf, the East Australian Current (EAC) and the coastal trapped waves (CTW).

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Synergy between In-situ and Altimetry Data to Observe and Study the Fine-Scale Dynamics in the Ligurian Sea (NW Mediterranean Sea)

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Historically, satellite altimetry has not been designed for observing the coastal ocean but, thanks to advances in the processing of the data and to technological innovations (Ka-band and SAR altimetry), more and more accurate altimetry sea level observations become available near land surfaces. As a consequence, we can easily assume that the use of this observational technique in coastal studies will be largely extended in the next years. The North-Western Mediterranean Sea (NWMed) has become a pilot area for coastal altimetry studies. It is a particularly interesting area in terms of coastal ocean dynamics, complex and associated with a large number of fine scale structures. Long time series of repeated in-situ datasets also exist in this area. Today, we know that only a small part of the NWMed ocean dynamics can be captured by satellite altimetry. Thus this is one of the ideal regions to investigate the progress made in coastal altimetry, and the perspectives it offers in terms of mesoscale and sub-mesoscale ocean observation.

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25-Year Altimetric Record #2: Global Mean Sea Level as a Key Climate Indicator

KEYNOTE: Improvements in Accurately Measuring Sea Level Change from Space and Expectations for the Future: an ESA Climate Change Initiative

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Over the last decade, the Global Climate Observing System (GCOS), in support of the UNFCCC, have put together a set of requirements for satellite data to meet the needs of the climate change community. These are broken down into key physical, chemical or biological variables of the Earth system, or 'Essential Climate Variables' (ECVs) as they are known. The goal is to provide stable, long-term, satellite-based ECV data products for climate modellers and researchers. To respond to this need for climate-quality satellite data, the European Space Agency (ESA) has set up a new programme, the ESA Climate Change Initiative (CCI) which started in 2010.

Sea level was one of the ECVs selected from the beginning of the programme 8 years ago: it is a very sensitive index of climate change and variability which integrates the ocean warming, mountain glaciers and ice sheet melting. Understanding the sea level variability and changes implies an accurate monitoring of the sea level variable at climate scales, in addition to understanding the ocean variability and the exchanges between ocean, land, cryosphere and atmosphere.

One of the objectives of this paper is to present the main improvements performed during the different 2 first phases of the project. During Phase I of the Project (2010-2013), the best altimeter algorithms have been selected for the production of a first set of sea level maps. During phase II of the Project (2014-2016), the time series has benefited from yearly temporal extensions. A full reprocessing of the monthly sea level maps was carried out and is now available for users. This new product benefits from the development of improved radar altimeter standards which have contributed to increase the sea level ECV homogeneity and to reduce the altimetry errors, consolidated with a thorough error characterisation. In addition, the climate modelling group has contributed to the assessment of the products. Specific tasks were undertaken to validate the sea level in coastal areas and to improve its estimation in the Arctic region.

We also present the road map in order to continue to improve sea level. Following the main conclusions of the project, the altimeter errors still require to be better characterised at different climate scales. It is also fundamental to keep on evaluating new altimeter standards and to recommend the best one so that the sea level ECV (now produced by the Copernicus Climate Change Service, C3S) remains a state-of-the-art product. In addition, some key scientific issues remain open. The estimation of the sea level evolution at the coast is one of them as it is still unclear if the sea level estimation provided by altimetry in the open ocean is representative of the actual evolution at the coast. Improving the altimeter sea level products in the Arctic Ocean also remains a high priority.

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Sea Level Rise as Measured by 11 Satellite Radar Altimeters

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That global mean sea level is rising by 3 mm per year is known for some time now, thanks to the reference altimeter missions TOPEX and Jason-1/2/3. Recently, a significant acceleration is being detected as well. However, there are significant questions to be raised about the validity of these measurements and their processing, without external verification.

Questions concerning, for example, the proper application (or not) of the Cal-1 correction of TOPEX, whether done for side A or side B or both, cannot be solved by choosing the approach that best fits our expectation. Only by diligent verification against tide gauges, or the suite of other altimeter around at that time can shed a better light on this.

This presentation thus attempts to combine the sea level records of all 11 satellite radar altimeters flying since 1992 (TOPEX, Jason-1/2/3, GFO, ERS-1/2, Envisat, CryoSat-2, SARAL/AltiKa, Sentinel-3A) and identify where and why they differ. It should not be forgotten that some of the anomalies in the instruments or processing of the reference missions were detected by their deviation from the other missions. All these data have been harmonised, with similar orbit solutions and geophysical corrections in the Radar Altimeter Database System (RADS).

For each of these missions we present comparisons against a global set of (about 75) tide gauges. Which are best fitting the tide gauge data? What is the best practice for correcting for vertical land motion at the gauges?

Further we verify the estimates of acceleration in the global mean sea level record. What is the goodness of fit for the individual altimeter missions? Can we properly judge the non-use of the Cal-1 correction to the TOPEX measurements?

Finally, we would like to point out some unanswered or lesser addressed questions regarding the construction of the global mean sea level. What is the best averaging method? What to do about the contribution of the Arctic region?

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A Review of the Global Sea Level Record Construction with 25 Years of Reference Missions.

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The CSIRO sea level record has continuously been updated over the years and is one of the reference calculations for science and the broader community. In this presentation we show the method employed to compute the record based solely on the reference missions from January 1993 to present. 2 methods are used using along-track and using pre-gridded data. A number of corrections assemblies is also generated to evaluate the sensibilities on all components of the range correction. We also use the global tide gauge network to evaluate individual missions bias drifts besides evaluating the absolute bias at our Bass Strait in situ absolute sea level site. The records we produce have recently been ingested in various analyses of the Global sea level record. Here we evaluate the impact of the components and method on the long-term signatures (trend and acceleration) and emphasize the need for revisiting the early record processing beyond the recent updates.

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Acceleration and Long Term Rise in Global Sea Level: A TOPEX Perspective

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As the first mission in the partnership between NASA and CNES for dedicated, high accuracy ocean altimetry, TOPEX/POSEIDON (1992-2005) forms a crucial part of the 25-year ocean climate record from altimetry, and the record of global mean sea level change. Recent work has suggested that estimates of global mean sea level based on existing, publicly available TOPEX/POSEIDON products seem to contain systematic errors on the order of 1 cm, which changed slowly throughout the mission. These must be removed or addressed in order to accurately estimate global sea level rise over the past 25 years.

Three features of the TOPEX data must be dealt with carefully in order to secure its contribution to the climate record. TOPEX/POSEIDON used three altimeters over its lifetime: TOPEX (NASA) Alt-A and Alt-B and the experimental CNES POSEIDON, forerunner of the Jason series. The transition from Alt-A and Alt-B did not have the benefit of overlap for cross calibration (other than the connection through the sparse POSEIDON cycles) as is available between Alt-B and Jason-1 and then others of the Jason series. The transition was necessitated by changes in the point target response (PTR) of Alt-A, most clearly manifested by an apparent increase in significant wave height (SWH). Finally, the TOPEX altimeters had certain waveform artifacts (“leakages”) that may have subtle effects on the measurements. Related to the latter two effects, there has been much recent discussion of the use of a TOPEX internal calibration (“Wallops/WFF correction”) that was not well understood previously.

We will discuss how these and other issues impact the TOPEX record of global sea level change. In particular, we will consider the impact of such errors on detection of an acceleration in global sea level rise during the 25 year record. Finally, we will discuss to what extent these issues might be mitigated in a comprehensive reprocessing of the data.

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Searching for Acceleration in Regional Sea Level Measurements

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25-years of satellite altimeter measurements has now allowed the detection of acceleration in the rate of global mean sea level change. As outlined in past studies, however, detecting acceleration in regional sea level change is more challenging because of additional contributors to regional sea level and generally larger variability. Here, we ask the question whether it is possible to detect an acceleration in regional sea level from the now 25-year altimeter record. Specifically, using the MEaSUREs satellite altimeter dataset, we determine where an acceleration in sea level may already be detectable given appropriate consideration of the contributors to regional sea level change during the altimeter record. We have removed an estimate of large-scale interannual and decadal variability and the impacts of the eruption of Mount Pinatubo, and then estimate the rate and acceleration of regional sea level change. We will discuss the results and compare to the acceleration that we might expect from Greenland and Antarctica as observed by GRACE.

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Synergy between Altimetry, Other Data and Models in Support of Operational Oceanography #2

Combination of AVISO/DUACS and Argo Data Sets to Follow the Evolution of Long Lived Eddies and their 3D Structure from 2000 to 2015 in the Mediterranean Sea.

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We build an unique database (DYNED-Atlas) of surface intensified eddies for a 15 year period (2000-2015) in two specific areas: the Mediterranean Sea and the Arabian Sea. This database contain the physical and the dynamical characteristics of mesoscale eddies detected from the cross analysis of DUACS gridded altimetric products (formerly distributed in AVISO, now in CMEMS) and Argo profiles. Among other characteristics the typical size, the intensity and the trajectory of each detected eddy were calculated. An iterative method was used on the AVISO surface geostrophic velocities in order to compute the cyclogeostrophic velocity components. The addition of these ageostrophic terms leads to a significant velocity increase for some mesoscale anticyclones. Then, the estimations of the three-dimensional eddy structures were deduced from the co-localization of surfacing Argo temperature/salinity data into altimeter-detected eddy areas.

We were then able to quantify the typical temperature, salinity and density anomalies associated to the recurrent mesoscale anticyclones which control the regional circulation of the Mediterranean Sea. We observed, during this 15 years period, that the long-lived anticyclones of the eastern basin have a much deeper extend that the Algerian Eddies. Moreover, we were able to reconstruct, with a high accuracy, the three-dimensional structure of few eddies that were surveyed by more than fifty Argo profiles. The comparison with other remote sensing images (SST and CHL) was also used to quantify the errors on the eddy detection, from DUACS altimetric maps, when the density of tracks is reduced. This study showed that the combination of DUACS products and the in-situ Argo data sets could provide a regional characterization of the three-dimensional structure of individual eddies, far beyond the classical composite eddy analysis.

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Influence of North Atlantic Teleconnection Patterns on Sea Level Anomaly of the North Atlantic Ocean and Seas around Europe

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In this study, a 20-year (1993-2013) record of multi-mission Sea Level Anomaly (SLA) monthly grids provided by the European Space Agency (ESA) Sea Level Climate Change Initiative (SL_cci) was used to analyze the relation between SLA and the most prominent climate patterns that act on the North Atlantic (NA) and on several seas around Europe at annual and inter-annual timescales, which are key time scales for studying the atmosphere-sea interaction in the climate system. These atmospheric modes of variability, or teleconnection patterns (TP), are expected to produce strong sea level variability and inter-annual fluctuations in the rates of sea level rise. The NA TP considered, which configurations and phases are well-known, were: North Atlantic Oscillation (NAO), Eastern Atlantic (EA), Eastern Atlantic/Western Russia (EA/WR), Scandinavian (SCA) and Polar/Eurasia (POL).

Despite the effects of these TP over the European and Northern American climatology, related with their associated winds, land temperature, rainfall patterns or atmospheric pressure values being deeply explored, their influence on SLA has not been fully analyzed yet. This study intends to contribute to the improvement of the knowledge of the Atlantic Ocean variability at basin-scale, by inspecting the response of the NA SLA to the NA main modes of variability, hence allowing a better understanding of the observed SLA changes and the atmosphere-ocean links that contribute to these fluctuations. The correlation between SLA and the TP was also inspected for several sub-basin regions as the North, Baltic, Mediterranean and Black seas.

Correlation maps between each TP and SLA, as well as composite maps of the main driven factors (sea level pressure, SLP; sea surface temperature, SST; wind field, WF) were produced to yield the results reported here. A solid SLA-TP connection and a strong long-period SLA fluctuation, both in spatial and temporal scales, were identified, revealing an important oceanic forcing of the atmosphere and allowing a better understanding of the observed SLA changes and the atmosphere-ocean links. Both the seasons and the geographic areas with the most significant correlations have been identified. The physical processes underlying SLA-TP correlations were also investigated.

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Summary of Results from CASSIS Project: Southwestern Atlantic Currents from In-Situ and Satellite Altimetry

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The CASSIS project is a French-Argentine cooperation to study the circulation in the Southwestern Atlantic from in situ and satellite altimetry data. Seven moorings that measure currents, temperature, conductivity and pressure and a fully equipped oceanographic buoy collected in situ data between December 2014 and May 2017. During the first year (December 2014-November 2015) the moorings were deployed below Jason-2 satellite altimeter track #26, covering the northern portion of the Malvinas Current (MC) and Patagonian continental shelf (PCS). In December 2015 the instruments were recovered and redeployed for a year and a half along a zonal section at 44.7ºS. A summary of the results obtained are reviewed here and in complementary presentations in this meeting (Artana et al, Lago et al, Paniagua et al, Ferrari et al). In-situ surface currents and geostrophic velocities obtained from satellite altimetry are significantly correlated at the shelf-break (0.7). In the continental shelf correlation is low and significant (0.3) only when the Ekman component is added to the satellite-derived velocity. During specific events associated with the presence of mesoscale eddies at the shelf-break and to the passage of synoptic storms at the continental shelf, differences between remote and in-situ currents are larger.

During the period of measurement, the MC at 41ºS can be characterized by two distinct regimes where along-slope velocities are either (i) large, surface-intensified or (ii) weak with almost zero vertical shear. The weak regime is due to an upstream retroflection of the Malvinas Current to the east. A large shift of the structure of the water masses accompany the along-slope velocity change: all water masses deepen and shift eastward during the weak regime. Thus, measurements show that the vertical structure of the water column is a critical information that is needed in the attempt to use satellite altimetry as a proxy of subsurface currents.

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Transport Efficiency of an Agulhas Ring from Combined Satellite Altimetry and Argo Profiles

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The Agulhas system links the Indian, Southern and Atlantic oceans. As such, it is a major regulator of the global climate. In particular, the leakage of warm saline waters from the Indian to the Atlantic ocean, the "Agulhas leakage", feeds the surface branch of the South Atlantic meridional overturning circulation (SAMOC). One of the main processes contributing to the transport of the leaked waters from South Africa to Brazil across the whole South Atlantic basin are Agulhas rings. These rings are among the largest and more coherent eddies in the world, with diameters of hundreds of km and life spans of more than 2 years.

To quantify the water transported by a specific Agulhas ring and the exchanges that occurred along its path, we synergistically exploited in-situ Argo profiles and remote-sensing altimetry. AVISO satellite-surface velocities showed that the eddy formed west of South Africa at the beginning of 2013 and reached the Brazilian continental shelf after almost 3 years. Argo profiles were used to reconstruct the 3-dimensional eddy structure along the track. Temporal variations of eddy-volume and eddy-core characteristics were used to assess and quantify the exchanges occurred with the surrounding waters.

Results showed that the eddy was at least 1500-m deep and that its dynamics was affected by the two main open-ocean ridges it encountered along its path. Between these ridges, the volume of the eddy was mostly conserved, but water were exchanged at an approximately constant rate. When the eddy begun to dissipate, volume losses and water exchanges were more pronounced at depth. These findings highlight the importance of combining surface with in-situ information to accurately representing the Agulhas ring transport and exchanges. Altimetry-based Lagrangian diagnostics indicated that, after an initial period of instability, at the surface the exchanged waters dispersed roughly in the same direction of the eddy, but with smaller velocities. Thus the most efficient transport of Agulhas-leaked waters occurred within the eddy. These insights improve our understanding of the effective contribution of the Agulhas leakage to the surface branch of the SAMOC.

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Radar Altimeters for Enhanced Polar Ocean Observations

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We present a review of several case studies where radar altimeters have been used to derive new insights into the Arctic and Antarctic oceanography. Over the last 8 years CryoSat-2 has allowed a radically new view of the ice covered Arctic and Antarctic Oceans, providing us with the first global view of the polar dynamic topography and geostrophic currents, under both ice covered in ice free conditions. Other geophysical quantities of interest have also been derived, ranging from Eddy kinetic energy, Ekman upwelling/downwelling, improved tidal models, significant wave height, or better resolved bathymetry at the bottom of the Ocean. We will illustrate some of the challenges in processing the radar signal in this highly complex sea ice covered regions with recent examples.

In the Arctic, merging Envisat and CryoSat-2 data, a timeseries of geostrophic currents was produced over the period 2003-present. This data were succesfully validated against in-situ observations from tide gauges and moorings. Similar products were devolopped in the Antarctic for the CryoSat period, 2010-present, and were also validated against similar in-situ observations. These results demonstrate the maturity and reliability of processing chains based on empirical retrackers. On the other hand, physical retrackers, have recently been proposed for improving the radar processing chain, both in the detection and classification and retracking steps. We will assess the degree of readiness of such approaches and use the retrieval of significant wave heights from CryoSat-2 as an illustration of their applicability.

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Advances in our Understanding of Coastal Processes #2

Coastal Sea Level Trends

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A significant part of the World's population lives in coastal areas affected by coastal sea level rise. Therefore, measuring accurately sea level rise right at the coast is of utmost importance.

The new generation of altimeters that employs the Delay-Doppler technique (DDA) (as implemented on CryoSat-2 and Sentinel-3, and likely all following altimetry missions) allows increasing along-track resolution dramatically, down to 350 meters, and is therefore able to monitor the coastal zone better than conventional satellite altimetry.

In this study we investigate the impacts of SAR data quality in the estimation of coastal sea level trends on selected regions worldwide.

First region of analysis is the North Eastern Atlantic shelf where SAR data coverage is seven years long and the absolute sea level trends can be compared to the tide gauge sea level trends corrected for vertical motion from co-located GPS stations. Data cover 18 months of Sentinel-3A (from June 2016 to December 2017) and seven years of CryoSat-2 (from October 2010 to December 2017). SAR products are from the ESA GPOD processor, SARvatore, for both CryoSat-2 and Sentinel-3A satellites and from the Marine Sentinel-3 processor. The coastal dedicated retracker SAMOSA+ is applied in both processors. Reduced SAR altimetry (RDSAR) is from the TALES and STAR in-house products and from the Marine Sentinel-3 product.

Trends in coastal in-situ and models data are also analysed. Ocean model data are from the operation BSH model and from the coupled Geestacht COAstal model SysTem GCOAS, in situ sea level and GPS data are from SONEL and BGK/BfG local organisations.

Other regions worldwide are considered and results are compared with sea level trends of the 25-year altimetric record.

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Under-Estimated Wave Contribution to Coastal Sea Level Change and Rise

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Coastal zones and communities are expected to be increasingly threatened by sea-level changes acting at various timescales, ranging from episodic extreme events to interannual-to-centennial changes and rise. Local sea level variations at the coast are induced by global to regional sea level variations due to glaciers and ice sheets mass loss and to ocean thermal expansion, and by coastal variations due to atmospheric surges, tides and wave set-up and swash.

So far, most studies of sea level impacts have focused on extreme events and have shown that waves are dominant contributors to these extremes. Few studies have analyzed impacts of long term (interannual and longer periods) sea-level changes on the coast, although at regional scales they highlighted the importance of the wave contribution. When performed at global scale, such long-term studies mostly overlook wave contributions. In addition, current decadal predictions and future climate projections of sea-level changes do not include changes in wave climate.

Here, we examine the relative importance of contributors to coastal sea level variations over the last 23 years at global scale with a focus on interannual-to-multidecadal variations. Considered contributors are the altimetric sea level (which accounts for the transfer of water mass from the cryosphere and land to the ocean, ocean thermal expansion, ocean circulations and the associated redistribution of heat, salt and mass), atmospheric surges (surface atmospheric pressure effects and wind set-up), tides, and wave set-up and swash (from wind-waves and swells).

Our estimates of the contributions to total sea level changes along open coasts robustly indicate that waves are not only important in explaining sea level extremes. Despite waves being transient by nature, they are also major contributors to interannual-to-multidecadal sea level changes at the coast due to the low frequency modulation of their characteristics related to wind changes due to both internal variability of the climate system and climate change. This result is regionally dependent, but for some regions the wave contribution can mask or enhance the effect of thermal expansion and ice mass transfer from land over unexpectedly long periods, of several decades. These results advocate for an inclusion of the up-to-now overlooked wave contributions in past, contemporary and future sea level changes at the coast. Indeed, waves will very likely contribute to future multidecadal sea level rise (e.g. horizon of 2030, 2050 and longer) and their low frequency contribution to sea level change at the coast should be considered especially to estimate flooding and possibly coastal erosion.

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Seamless Geoids across Coastal Zones: Comparison of Satellite and Airborne Gravity across the Seven Continents – and an Azores Heritage Case

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An accurate coastal geoid model is important for determination of near-shore ocean dynamic topography and currents, as well as for land GPS surveys and global geopotential models. Since many coastal regions across the globe are regions of intense development and coastal protection projects, precise geoid models at cm-level accuracy are essential. The only way to secure cm-geoid accuracies across coastal regions is to acquire more marine gravity data; here airborne gravity is the obvious method of choice due to the uniform accuracy, and the ability to provide a seamless geoid accuracy across the coastline.

Current practice for gravity and geoid models, such as EGM2008 and many national projects, is to complement land gravity data with satellite radar altimetry at sea, a procedure which can give large errors in regions close to the coast. To quantify the coastal errors in satellite gravity, we compare results of a large set of recent airborne gravity surveys, acquired across a range of coastal zones globally from polar to equatorial regions, and quantify the errors as a function of distance from the coast line for a number of different global altimetry gravity solutions. We find that accuracy in satellite altimetry solutions depend very much on the availability of gravity data along the coast-near land regions in the underlying reference fields (e.g., EGM2008), with satellite gravity accuracy in the near-shore zone ranging from anywhere between 5 to 20 mGal r.m.s., with occasional large outliers; such errors may typically propagate into coastal geoid errors of 5-10 cm r.m.s. or more, and highlight the needs for airborne gravity surveys in the coastal zones.

One of the first examples of such a dedicated effort is the Azores airborne gravity campaign, carried out more than 20 years ago as part of the AGMASCO (Airborne Geoid Mapping System for Coastal Oceanography) EU project 1996-98.

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The Impact of Satellite Altimeter Observations on Estimates of Cross-Shelf Fluxes in the Mid-Atlantic Bight

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Satellite altimeter observations form an important component of ocean observing systems in the coastal ocean and, along with other satellite and in situ measurements, can be used to constrain ocean models using data assimilation methods. We present here a quantitative assessment of the impact that various recent altimeter missions have on estimates of cross-shelf fluxes of mass, heat and salt in the vicinity of the shelf-break front in the Mid-Atlantic Bight when these data are assimilated into the Regional Ocean Modeling System (ROMS). The data assimilation method used is a 4-dimensional variational (4D-Var) approach, and using techniques employed routinely in numerical weather prediction, the 4D-Var transport increments can be partitioned into contributions from each observing platform. The impact of coastal satellite altimeter measurements on the cross-shelf transport will be assessed and compared to the impact of other elements of the coastal ocean observing system. We will also demonstrate how data from particular satellite systems can be flagged if it appears to be producing a disproportionately large impact on the circulation estimates. In addition, local and remote influences of altimetry on the cross-shelf transport will be demonstrated

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Can Ocean Temperature Changes around the Greenland Ice Sheet be Inferred with Altimetry

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Net mass loss of the Greenland Ice Sheet is significantly contributing to global sea level rise. Some of Greenland's net ice loss is likely due to increased melting of its marine-terminating glaciers from warming ocean waters. Oceanographic observations in the ocean basins of the northwest North Atlantic show large decadal variations of ocean temperature and salinity in the upper 2000 m. Waters in these basins transitioned to a warming phase in the late 1990s and for more than a decade thereafter many of Greenland's glaciers were observed to retreat, accelerate, and thin. Linking the observed glacier changes to ocean warming remains challenging because very few in situ ocean observation exist on the shallow continental shelf between the ice sheet and the offshore ocean basins. Here, we report on progress using satellite altimetry to infer thermosteric variations on the continental shelf during this time period. Our project uses remote sensing and in-situ data, including satellite altimetry, numerical modelling, and data assimilation to characterize and reconstruct the ocean state in this region over the past 25 years. This three-dimensional time-varying reconstruction of the ocean state will allow us to determine (1) how have ocean temperatures immediately adjacent to the ice sheet changed? and (2) to what extent can satellite altimetry be used to infer ocean temperature changes in the region? Our work will pave the way for future monitoring of ocean thermal forcing of the Greenland Ice Sheet using sea surface height data from the upcoming SWOT, Sentinel-3, and Jason-CS missions

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25-Year Altimetric Record #3: Ongoing Scientific and Technical Challenges

REVIEW: 25 years of Sea Level Records from the Arctic Ocean Using Radar Altimetry

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In recent years, there has been a large focus of the Arctic due the rapid changes of the region. The sea level of the Arctic Ocean is an important climate indicator. The Arctic sea ice is decreasing and has since 1997 experienced a steepening in the decrease. The Arctic sea level determination is challenging due to the seasonal to permanent sea ice cover, the lack of regional coverage of satellites, the satellite instruments ability to measure ice, insufficient geophysical models, residual orbit errors, challenging retracking of satellite altimeter data. We present the DTU/TUM 25-year sea level record based on satellite altimetry data in the Arctic Ocean from the ERS1 (1991) to CryoSat-2 (present) satellites. The sea level record is compared with several tide gauges and other available partial sea level records contributing to the ESA CCI Sea level initiative. We use updated geophysical corrections and a combination of altimeter data: REAPER (ERS1), ALES+ retracker (ERS2, Envisat), combined Rads and DTUs in-house retracker LARS (CryoSat-2). The ALES+ is an upgraded version of the Adaptive Leading Edge Subwaveform Retracker that has been developed to improve data quality and quantity in the coastal ocean, without degrading the results in the open ocean. ALES+ aims at retracking peaky waveforms typical of lead reflections without modifying the fitting model used in the open ocean. Finally, we discuss the seasonal and regional variations over the past 25 years in the Arctic sea level.

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Towards a Methodology for Estimating Extreme Return Levels and Its Climate Variability of Coastal Sea Level from Satellite Altimetry

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The estimation of extreme water level values on coastal areas is a requirement for a wide range of engineering and coastal management applications. There are many coastal locations where there are no in-situ records or the local records cover only a few years. In this study, a novel method is proposed for the analysis of coastal extreme sea level through the use of satellite altimetry data.

Nowadays the accumulating altimeter records of several satellite missions from the 1990's offer a database with a span of more than twenty five years. Aside the well-known issue of altimeter measurements very close to the coast (e.g. corruption by land, wet troposphere path delay errors and local tide effects on the coastal area), there are other aspects that have to be considered when sea surface height values estimated from satellite are going to be used in a statistical extreme model. They are the use of an along-track and inter-calibrated multi-mission product to get long observed time periods since altimeter observations do not provide values uniform in time and space.

In this study we propose a method to estimate extreme quantiles (e.g. 50 year return period) by using a non-stationary extreme model which allows also to characterize the seasonal, interannual and long term changes climate variability of extreme sea levels.

The method consists of: (i) a pre-processing of the non-tidal residual database from the altimetry information; (ii) the selection of the satellite values within a geographic area around the coastal location; (iii) the regression of time-dependent extreme model and, finally (iv) the application of a scale coastal factor.

The scale factor depends on geographical characteristics of the coastal location, such as coastal exposure or width of the continental shelf. The methodology has been calibrated on the east US coast and has been applied and validated in other continental locations that do not have in-situ records.

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Understanding the Relation between Sea Level and Bottom Pressure Variability: Recent Progress and Future Challenges

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Inferring full information from sea level records, including details on internal ocean variability and changes in heat and freshwater content, requires accurate knowledge of bottom pressure fields. The availability of 25 years of altimeter data, and more recently satellite gravity and Argo data, together with developments in global and regional ocean modeling, has led to many efforts to assess the complex relation between sea level and bottom pressure, which is strongly dependent on time/spatial scales and location. Here we review recent advances and remaining challenges in the topic, drawing from a variety of regions and dynamical regimes. In forcing regimes such as the inverted barometer response to atmospheric pressure, sea level changes may be isostatic, with no significant imprint on bottom pressure. Inverted barometer signals are responsible for substantial variability in sea level but can be effectively removed using available atmospheric pressure fields. Once isostatic corrections are applied, observations reveal the importance of bottom pressure to explain sea level variance from sub-monthly to interannual time scales in many deep ocean regions. In addition, a considerable portion of the observed coastal sea level variability at monthly and longer time scales can be ascribed to variations in bottom pressure. Similar findings apply to semi-enclosed seas such as the Baltic or Hudson Bay. Sea level and bottom pressure changes become more similar as one moves poleward, consistent with the tendency for more barotropic dynamics at higher latitudes. In the tropics, baroclinic variability associated with Rossby waves and other processes can be seen in both sea level and bottom pressure. Improving current understanding of the relation between sea level and bottom pressure variability and relevant dynamics will require satellite measurements with better accuracy and spatial resolution, particularly in shallow coastal regions and semi-enclosed seas. Equally important is to explore high resolution models to gain new insights on the effects of small-scale topography and coastal geometry, as well as sub/mesoscale eddies. Consideration of different physics, including for example the use of non-Boussinesq formulations and inclusion of self-attraction and loading effects, will also be needed.

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25 years of Wet Tropospheric Correction: Long Term Stability Assessment Using Double Difference Method

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The wet tropospheric correction (WTC) is a major source of uncertainty in altimetry budget error, due to its large spatial and temporal variability. It also contributes significantly to the uncertainty in the long term mean sea level trend.

At the occasion of the 25 years of satellite radar altimetry, the long-term stability is addressed through the analysis of all the available timeseries of the microwave radiometer data in their most up-to-date reprocessing state: from TOPEX/Poseidon, Jason-1 to Jason-3 series, the ERS-1, ERS-2, Envisat, Sentinel-3A series, and AltiKa.

In order to better quantify the WTC trend, it is important to focus on the detection of potential instrumental drifts. The long-term stability of each radiometer is here assessed using the double difference method. The double difference accounts for frequency, Earth Incidence Angle, and orbital differences between platforms. To calculate the double difference, the single differences for each radiometer are first computed. The single difference is found by taking the difference between a reference statistic of the observed radiometer brightness temperatures (TBs) and a reference statistic from simulated TBs. The double difference is then the difference between the single differences of the two radiometers [1].

Single differences suffer from the discontinuities introduced by evolutions of the Numerical Weather Prediction model due to improvements in the operational version or modification of the assimilation scheme. By construction, double differences cancel out the impact of these evolutions.

Once the long-term stability of TBs is assessed, robust conclusions can be drawn on the stability of the WTC.

[1] R. A. Kroodsma, D. S. McKague, and C. S. Ruf, “Inter-calibration of microwave radiometers using the vicarious cold calibration double difference method,” IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., vol. 5, no. 3, pp. 1006–1013, 2012.

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Sea State Bias: 25 Years on

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Twenty five years on, Sea State Bias (SSB) remains the largest error in altimeter sea level measurements. In this update of the "Sea State Bias: 20 years on" review presented at the "Fifteen years of progress in Radar Altimetry" symposium in Venice in 2006, we consider how, and how much, our understanding of sea state bias has evolved over the past decade. From early empirical corrections to complex theoretical frameworks to present-day three-dimensional non-parametric models, have we now reached a consensus on how best to mitigate this tenacious problem? This presentation will seek to provide a comprehensive overview of the status of SSB estimation today. Looking ahead, we consider the new challenges raised by the changing sensitivity of errors to sea state as the altimeter constellation gradually evolves towards SAR mode altimetry, and by the effects of sea state off-nadir on wide-swath altimetry. Long-established validation practices come once again to the fore to help understand and characterise biases and correlations in altimeter sea level, waves and wind on global, regional and local scales through multi-platform comparisons and independent consistency checks. Finally, as new climate-related initiatives bring renewed attention on developing long term altimeter data records for the Essential Climate Variables for Sea State as well as Sea Level, we ask how to reconcile the trends and variability in sea state observed with altimetry, with those observed by other means and other mission types.

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Synergy between Altimetry, other Data and Models in Support of Operational Oceanography #3

Assimilation of High-Resolution Altimetry in a 2-km Canadian East Coast Forecasting System

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A new Government of Canada initiative called the Ocean Protection Plan seeks to provide a world-class capacity in emergency environmental prediction. A significant component of this project is the development of high-resolution coastal and near-shore ocean analysis and forecasting systems. Coastal ice-ocean prediction systems are being developed for the Canadian east and west coasts on 2-km resolution grids. A critical aspect of these systems is their capacity to accurately capture mesoscale and sub-mesoscale features for drift prediction applications. The assimilation of a high-resolution coastal altimetry dataset is essential to be able to adequately constrain these features.

For this purpose, a multi-mission high-resolution altimetry chain has been set up over the Canadian Eastern Seas, from the US border to the Baffin Bay [95°W-43°W; 42°N-82°N]. A regional tuning has been done in terms of corrections and reference surface. Issued from the most recent research activity in altimetry field, a new estimation of the satellite-sea distance based on the waveform classification has been proposed for the satellite mission Jason-2 and SARAL/Altika missions. For the satellite mission Cryosat-2, data measured by its Synthetic Aperture Radar (SAR) mode have locally been used when available. A dedicated data selection strategy has been developed for this regional production in order to take more precisely into account the seasonal ice coverage. It provides a good compromise between the quantity of observations and their variance reduction. A dedicated spatial filtering has been applied on native 20Hz/40Hz observations to remove their noise level. The choice of the cut-off length has been done on the basis of a regional spectral analysis. Each mission has been considered separately.

This paper will present a quality assessment of the high-resolution altimetry data set optimized for the observation of small scale oceanic structures near the Eastern Canadian coasts and in sea ice areas, with a particular attention on to the Gulf of St Lawrence and Grand Banks areas. This paper will also present the impact of assimilating this dataset in both the Canadian Regional Ice-Ocean Prediction System (RIOPS) (at ~6km resolution) as well as in a higher-resolution (2km) coastal prediction system. The ocean analysis component of the system is the System d'Assimilation Mercator version 2 (SAM2), which uses a multivariate reduced-order Kalman filter that assimilates sea level anomaly, sea surface temperature and in situ profiles of temperature and salinity. A particular focus is on the use of Dynamic Atmospheric Correction and Long Wave Error terms and the downstream impact on drift prediction.

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Toward New Validation Concept for High-Resolution and Coastal Altimetry: Application to the Ligurian Sea

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This study is a preliminary contribution to the European Space Agency effort to establish Reference Measurements of in-situ network for validating Coastal Altimetry. This shall consist in independent, fully characterized, and traceable in situ measurements that follow the principles outlined by the GEO/CEOS Quality Assurance framework for Earth Observation. In this respect, the proposed paper addresses to cross-compare and exploit conjointly new high–resolution altimetry data and in situ measurements acquired over coastal regions characterized by complex, small-scale and rapidly evolving oceanic features. We take advantage of using several kinds of multi-sensor in situ observations exactly collocated along SARAL/AltiKa and Jason-2 tracks. The main objectives are to assess new coastal altimetry processing technics and sensors while better understanding the differences with in situ measurements respectively due to physical content inhomogeneity and due to instrumental or data processing limitations. The obtained results show a remarkable agreement, especially between altimetry and Moving Vessel Profiler measurements over spatial scales of few tens of kilometer, paving the way for the definition of innovative science-oriented diagnostics particularly relevant for high resolution altimetric satellite missions

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A New Synergetic Approach for the Determination of the Sea-Surface Currents in the Mediterranean Sea

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We present a new method for the remote retrieval of the sea-surface currents in the Mediterranean Sea.Combining observations from multiple satellite sensors, we created daily L4 high-resolution maps of sea-surface currents, merging sea-surface height (SSH) and temperature (SST) data. The quality of the new multi-sensor currents has been assessed through comparisons to other surface-currents estimates, as the ones obtained from ships. Automatic Identification System (AIS), HF-Radar-derived currents in the Malta-Sicily Channel and ocean numerical model outputs. The study evidenced that our synergetic approach can improve the present-day diagnostics on the surface-currents in the Sicily Channel area. Indeed, assuming HF-Radar estimations as a reference, the merged SSH/SST currents exhibit smaller RMS errors than altimeter data, mainly due to their enhanced spatial and temporal resolution and to their capability of reproducing ageostrophic phenomena (like e.g. upwelling). The improvements are also found with respect to the model-derived currents. Moreover, the results of the comparative study proved to be very satisfactory using the AIS-derived data. The main perspective of this work, focused on the Mediterranean area, is the construction of hourly high-resolution currents which could be validated using both HF-Radar multiple platforms and in-situ measured hourly data.

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Continuous Transition of Kinetic Energy Spectra and Fluxes between Mesoscale and Submesoscale

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We present the kinetic energy spectra and fluxes of currents observed from multiple platforms off the U. S. West Coast -- satellite altimeter (ALT), high-frequency radar (HFR), and shipboard acoustic Doppler current profilers (ADCPs). The one-dimensional wavenumber-domain kinetic energy spectra of the HFR-derived surface currents agree with those of the ALT-derived geostrophic currents at scales larger than 100 km, and decay with k^{-2} and k^{-3} at high wavenumber (below 100 km) up to the wavenumber of 0.5 km^{-1}. Moreover, the kinetic energy spectra of subsurface currents obtained from shipboard ADCPs support a continuous transition of energy between mesoscale and submesoscale. A comparison of the kinetic energy fluxes, estimated from the gridded ALT-derived geostrophic currents and submesoscale HFR-derived surface currents, exhibits the potential injection scales of $\it{O}$(100) km and $\it{O}$(10) km, which are consistent with the regional Rossby deformation radius and the dominant length scales of the regional submesoscale eddies, respectively.

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The Malvinas Current System from 25 years of MERCATOR-Ocean Operational Reanalysis: Fronts, Recirculation Cells, Vertical Motions and Blocking Events.

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Daily outputs from the Mercator-ocean (1/12°) global operational reanalysis are analyzed in the Malvinas Current (MC) system. The performance of the model is evaluated over the last 25 years using satellite altimetry, Argo float and mooring data. Model outputs are compared to in situ mooring time series of velocity, temperature and salinity gathered over the Patagonian Shelf break at 41°S (at three different times:1993-1995, 2001-2003 and 2014-2015) and at 44.7°S (2015-2017). Comparisons show that the model reproduces correctly the general circulation and the complex hydrographic features of the study area including the vicinity of the Brazil-Malvinas Confluence. The model accurately matches the observations.

The model outputs are then used to examine the signature in potential density at 450 m and in absolute dynamic topography (ADT) of the major fronts of the MC System. We identify isolines of ADT and potential density at 450 m associated to the mean front location and establish their correspondence to specific water mass boundaries. Frontal displacements as depicted in satellite ADT, model ADT and model potential density at 450 m along the MC present a remarkable agreement. The potential density field at 450 m is an excellent indicator for the synoptic mapping of the MC system fronts. It makes possible the detection and tracking of eddies shed by Polar Front that feed the MC and have a much weaker signal in the ADT. The cyclonic eddies shed by the Polar Front contribute to the variability of the MC at 41°S and to the MC recirculation cell.

The density field is sensitive to horizontal and vertical motions of the water column. Empirical orthogonal functions of density and velocity fields of model outputs show the relationship between the water mass distribution of the water column and the intensity of the MC during upwelling and downwelling events on the continental slope.

Blockings events of the MC at 48°S are a recurrent feature of the MC circulation (about 26 events over the 25 year altimetry record, Artana et al., 2016). During these events the MC downstream does not collapse rather becomes the western boundary of a robust recirculating cyclonic cell. Model outputs document the genesis and the vertical structure of the blocking events.

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Outlook #1: Sea Level and Ocean Circulation: Continuity and Improved Resolution

Sentinel-3A Contribution to the Continuity of Sea-Level Rise

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Sentinel-3 is part of a series of Sentinel satellites responsible for taking care of a continuous ‘health check’ of the Earth planet under the umbrella of the Copernicus program. The main objective of the Sentinel-3 mission is to monitor the marine environment. The Copernicus program will launch four Sentinel-3 satellites (from A to D) to achieve this goal from 2016 to 2022. Since Spring 2016 Sentinel-3A has been successfully contributing to the continuity of the sea level climate data record . During the lifetime of the mission its processing baseline has considerably evolved having positive impacts in the data quality. This presentation is intended to provide an overall description of the topography scientific capabilities of Sentinel-3 satellites, as well as provide an up to date Sentinel-3A marine center data quality assessment from the latest reprocessed data in a multi-mission setting. The latter shall allow for revisiting the status of the Jason-3 and Jason-2, in comparison with Sentinel-3A. To this goal this presentation aims at: providing multi-mission time series of the main climate records (sea level, significant wave height and wind speed); quantifying cross-overs (mono- and multi- mission); as well as provide more than two year global assessment of SAR mode versus Pseudo-LRM.

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The Sentinel-6/Jason-CS Mission

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The threat of sea level rise to coastal communities is an area of significant concern for Governments and policymakers on the global stage. The well-being and security of future generations depend on actions and decisions on environmental policies that are being made now. To ensure decision makers and policy makers have timely and easy access to the best information on aspects of societal relevance, including sea level rise, the European flagship Copernicus programme has been established to provide environmental information to understand how our planet and its climate are changing, the role of human activities in these changes and how these will influence our daily lives.

The Sentinel-6/Jason-CS mission is primarily designed to measure global sea level change and variability by ensuring continuity and extended capability of the satellite altimetry measurements (sea surface height) derived from the TOPEX/Poseidon and three consecutive Jason missions without degradation in precision or accuracy. It will take the role of the reference mission in the CEOS-coordinated virtual constellation of ocean surface topography missions and will be operated in synergy with Copernicus Sentinel-3 forming the Copernicus Altimetry Constellation. Sentinel-6/Jason-CS is a cooperative mission with contributions from NASA, NOAA, ESA, EUMETSAT, CNES, and the European Union (EU).

Sentinel-6/Jason-CS consists of two identical satellites flying in sequence designed to provide near-real-time measurements to operational users of sea surface height, significant wave height, and wind speed to support operational oceanography and climate monitoring. As a secondary objective, the mission will also include Radio Occultation user services and has the capability to determine the height of inland waters. The mission includes a state of the art satellite platform hosting a new dual-frequency (C and Ku band) synthetic aperture radar (SAR) altimeter (Poseidon-4), an improved microwave radiometer (AMR-C) to secure operational continuity of the long-term ocean surface topography climate data record until the early 2030's. Poseidon-4 operates in a new "interleaved mode" providing measurements of both Low-Resolution Mode (LRM) and SAR at the same time. Each satellite will be launched sequentially into the 'Jason orbit' (up 66° latitude) with a 12-month overlap of its A-unit and Jason-3 to understand the impact of Poseidon-4 SAR mode with respect to the historical LRM time series. The launch of the A and B satellites are planned for 2020 and 2025, respectively.

Within Copernicus and together with other satellite altimetry missions, the twin-satellite polar-orbiting Sentinel-3 and the Sentinel-6/Jason-CS reference missions will work together to monitor global sea level changes and ensure a complete record of sea level for the coming decades.

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Observing the Ocean Surface Topography at High Resolution by the Surface Water and Ocean Topography (SWOT) Mission

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This paper presents the oceanographic objectives and plans of calibration and validation, science investigations and applications for the Surface Water and Ocean Topography (SWOT) Mission. This international mission, planned for launch in 2021, will make high-resolution observations of the ocean surface topography as a next-generation altimetry mission utilizing the technique of radar interferometry. With measurement over a swath of 120 km (20 km nadir gap), SWOT will map the entire earth within +/- 77.6 degree latitudes every 21 days. Over the ocean, this new measurement will extend the two-dimensional resolution of ocean surface topography estimated from conventional radar altimetry from 150 km wavelength to possibly 15 km, offering opportunities to study the oceanic dynamic processes at these scales that act as one of the main gateways connecting the interior of the ocean to the upper layer. These processes provide both sink and source for the kinetic energy at larger scales, involving both low-frequency geostrophically balanced motions and high-frequency internal tides and gravity waves. The active vertical exchanges linked to these scales are a key aspect of the role of the ocean in the climate system. These vertical exchanges have impacts on the local and global budgets of heat, carbon and nutrients for biogeochemical cycles.

To mitigate the challenge of the temporal sampling, the first 90 days of the mission after the commissioning phase for engineering check-out and adjustment will be flown in a 1-day repeat fast-sampling phase for calibration and validation. This much improved temporal sampling will allow enhanced understanding of the measurement at 15-150 km wavelengths in terms of signals and measurement errors. In particular, there will be two measurements a day at the crossover diamond-shaped regions, where the two-dimensional measurement at twice daily interval will provide the maximum amount of information on rapidly changing signals and errors. During the calibration and validation phase, in-situ observations of the dynamic height of the ocean will be deployed to evaluate the relationship of the sea surface height measurement to the internal processes of the ocean. An airborne lidar system will also be flown to measure the sea surface height for comparison to the satellite observations.

The mission's science team was selected in 2016 with renewal expected in 2020. The topics of oceanographic investigations cover mesoscale and submesoscale processes; modeling and data assimilation; tides, waves, and high-frequency processes; calibration and validation; coastal and estuarine processes. Because the challenges posed by the coarse temporal sampling and measurement errors, it is expected that the science investigation will heavily depend on modeling and assimilation for the construction of high-level gridded products. Various efforts are being made to meet the challenges, involving modeling low-frequency balanced motions and high-frequency tides and internal gravity waves and their assimilation by the models for construction of the state of the ocean in both space and time.

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Development of Hydrologic Science and Applications from the Surface Water and Ocean Topography (SWOT) Mission

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The Surface Water and Ocean Topography (SWOT) satellite mission, a joint project of NASA and CNES, aims to provide the first simultaneous, space-based measurements of inundation extent and water surface elevation in rivers, lakes, and wetlands around the world. SWOT aims to observe rivers as narrow as 50-100 m and lakes as small as 0.01-0.06 km2, with height accuracies of ~10 cm for water bodies 1 km2 in area. Using SWOT measurements of temporal variations in the height, width, and slope of rivers, several algorithms have been developed to estimate river discharge solely from SWOT measurements. Additionally, measurements of lake height and area will allow estimation of variability in lake water storage. Development of SWOT science and applications began more than a decade ago, and over that time period our understanding of the science that it will enable, and the applications of that science, have evolved. In this presentation, we explore this evolution, focusing on new results developed by the SWOT Science Team, including improvements in SWOT river discharge algorithms, assimilation of simulated SWOT data into hydrodynamic models, examination of SWOT's role in quantifying variations in surface water storage, and anticipated application of SWOT data to problems related to transboundary rivers, water resources, and flood forecasting.

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On the Spatial Scale of the Future SWOT KaRIN Measurement over the Ocean

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Data fusion and big-data analytics of observational and simulation data will be the very basis of efforts to understand and protect the Alps, as they are exceptionally endangered by climate change. The Virtual Alpine Observatory (VAO) collaboration with its motto "Monitoring – Understanding – Prediction – Action" brings together data and models from heterogeneous sources, supporting science and administrative decision making.

Within the "Computing on Demand" (CoD) section of the AlpEnDAC portal, simulations can easily and interactively be triggered through a web GUI. One of the services is to provide simulations of Lagrangian air mass propagation. Several transport codes [FLEXTRA, FLEXPART (Stohl et al.) and HYSPLIT] have been incorporated after being optimized and adapted. They help to reveal in which large-scale transport regime a selected observation was (or will) be conducted.

Validation of satellite instruments "on demand" and in near-real time will be one the upcoming focal points in AlpEnDAC. Especially Sentinel-5P will provide an unprecedented amount of highly resolved trace gas information. In collaboration with domain scientists, the intrinsic differences of in situ and space borne instruments will be addressed to make both measurements comparable.

Our mission is to make alpine scientists profit from the Copernicus programme, giving them low-threshold access to a modern data management and analysis platform, where traditional HPC is fused with Big-Data analytics. The VAO, with participating institutions in Austria, France, Germany, and other alpine countries is an ideal field for our efforts, funded by the Bavarian State Ministry of the Environment and Consumer Protection.

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Advances in our Understanding of Wave Observations and their Applications

KEYNOTE: From Azores to Azores, 100 Years of Wave Observations for Forecasting: A Living History and Challenges Ahead

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In 1918, Louis Gain proposed a method for forecasting swells arriving in Morocco, based on observations made in the Azores. These 6-hourly observations were organized by Afonso Chaves, at the Azorian Meteorological Services, and allowed a "Swell forecasting center" to be established in Casablanca, starting activities in 1919 (Gallois 1922), with the goal of optimizing the port operability. What had started as a scientific collaboration between the Portuguese and French navies, was a first step dealing with swells, which are still today the most difficult part of the sea state to predict. Swells radiate from distant storms and, although they may only cause some discomfort in the open ocean, they are a dominant source of coastal hydrodynamics, contributing to extreme sea levels in the Caribbean or the West Pacific, and driving longshore currents and coastal erosion. Swells with periods longer than 13 s lose little energy during their propagation across ocean basins whereas shorter swells decay faster (Snodgrass et al. 1966). This effect was better quantified thanks to the "wave mode" data from European Synthetic Aperture Radars-SARs-(Ardhuin et al. 2009). The physical process which causes this dissipation is still debated. The authors believe it to be air-sea friction (Semedo et al. 2009) but it is very weak locally.

Satellites are now the main source of sea state observations and sea state corrections are needed in the remote sensing of many essential climate variables: sea level, wind, surface salinity… In particular the limiting factor in the accuracy of sea level measurements is the sea-state bias that cannot be fully described by the two parameters (wave height and backscatter) measured by nadir altimeters. Future progress in altimetry will thus require a more complete characterization of the sea state, and work in this direction is underway with the CFOSAT, SWOT and SKIM missions.

The propagation of swells from Azores to Casablanca allowed our predecessors to make the first measurements of swell dissipation, which were used by Sverdrup and Munk (1947). One of the last feats of the Casablanca group was the development of the first numerical wave model "DSA" (Gelci et al. 1957). That model computed the evolution of the wave spectrum in space and time, a method that is still used in today's WAM or WAVEWATCH III models ran operationally around the world with remarkable accuracy at scales larger than 200 km or so. Swells can be observed from space and this year's launch of CFOSAT will mark a new era in the mapping of waves and in particular swells worldwide. CFOSAT will combine a classical nadir-beam altimeter with off-nadir beams from which the directional wave spectrum can be measured without the blurring effect of SARs.

Ongoing work spurred by the SWOT mission is revealing that currents all across oceans are the dominant source of small scale variability in the wave field (Ardhuin et al. 2017). Future observations, analysis and numerical modelling, now pushing to higher resolution will thus require a combined investigation of winds, waves and currents.

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Incorporation of the Satellite Altimetry to the Wave Analysis, Forecast, and Verification at NWS

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The National Centers for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA) provides the operational wave forecast and guidance for the U.S. National Weather Service (NWS). For the last two years, as part of ongoing efforts to improve the operational wave products, there is a significant push to incorporate the available altimeter sea state observations into the various operational systems.

Currently, altimeter observations from JASON-2 and -3, CRYOSAT-2, SARAL/ALTIKA and SENTINEL-3 are used in the wave field analysis, in the wave forecast verification and as well in the quality monitoring of the wind field used for the wave model forcing. This presentation focuses on the wave assimilation systems and wave validation applications.

Two wave analysis systems were developed with the capacity to assimilate the altimeter observations for the significant wave height: i) The 2D-var UnRestricted Mesoscale Analysis (URMA) which provides hourly 2D analyses of near-surface variables for the Contiguous USA, Hawaii, Alaska and Puerto Rico, with 2.5 km grid-spacing and ii) The global wave analysis system, which provides analysis of significant wave height for the deterministic forecast based on the Local Ensemble Transform Kalman Filter (LETKF-Waves) and the global wave ensemble system. Both systems, independently of the assimilation algorithm demonstrate positive impact: the bias of the analysis has been almost eliminated O(10-2)m and a reduction in RMSE by approximately 50%, which translates to 15% error reduction in the wave height forecast.

The altimeter sea state data are the primary input to the verification system for the significant wave height, named ObsOpWaves. The validation system is operationally ready and currently is used on demand. The ObsOpWaves has been used for the validation of the different operational systems: global and regional deterministic and ensemble wave forecasts but also of particular interest, such as hurricane wave forecast. These verification case studies not only provide a new perspective on the wave model accuracy discussion but also the wave verification methods.

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Detection of Ocean Whitecapping and its Variability Using Jason Radiometer and Radar Datasets

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The Jason series satellite ocean altimeters carry both a dual-frequency radar altimeter and a three-frequency microwave radiometer that provide coincident ocean surface measurements. This study examines the signature of ocean whitecapping (W) inferred from the nadir-viewing radiometer data, where this specific platform is expected to provide several advantages over off-nadir radiometer datasets more typically considered in ocean foam studies. Key benefits include coincident and highly accurate measurements of significant wave height and surface roughness obtained from the altimeter, and a simplified geophysical model where emissivity change due to surface tilting by longer-scale waves should be negligible. Predicted ocean emissivity is then due solely to additive short-scale roughness and foam-related terms. Combined radar and radiometer data are used to derive a new model for ocean whitecap coverage at 18 and 34 GHz that falls within the range of recent field studies and which suggests measurably lower whitecap coverage at 34 GHz than that proposed using off-nadir Windsat satellite data. Data also suggest less whitecap coverage than for either of the existing X- or Ka-band Windsat-based models at moderate wind speeds that dominate the tropics. Additionally, the radar data provide a clear means to document that 30-40 % variability in W at a given wind speed can be explained by variation in the mean square slope of intermediate scale gravity waves that lie in the Phillips equilibrium range. This result is consistent with several recent in situ field studies of whitecap variability, with theory for wind-wave dissipation due to breaking, and a first identification of this correlation using satellite data.

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Radar Altimeter Wind and Wave Data-Delay Doppler versus Conventional

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Radar altimetry has been carried out in a conventional low bit rate mode (LRM) since the start of space-borne radar altimetry more than 25 years ago. The pioneering CryoSat mission launched the new era of delay-Doppler radar altimetry (also known as SAR altimetry). While CryoSat-2 ocean coverage while operating in delay Doppler mode is limited to few ocean regions like the mid Pacific and the north-eastern Atlantic, Sentinel-3A (is part of the EU Copernicus programme) had the lead in global coverage. With more than two years of global Sentinel-3A delay-Doppler surface wind speed and significant wave height data, it is timely to make a comparison against conventional altimetry data from Jason-3 and possibly from Sentinel-3B which is planned to operate in conventional altimetry mode for few cycles possibly during the summer of 2018 while orbiting the Globe in tandem with its older sibling Sentinel-3A (several seconds apart).

The latest reprocessed Sentinel-3A data will be used in this extensive assessment. Comparison against Sentinel-3B LRM data, if made available in good time, will be done on a one by one bases. Jason-3 data will be used to represent the conventional altimetry data for comparison. Other conventional altimetry data may be used as well. ECMWF model products and in-situ (buoy) data will be used for the assessment.

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Review: Toward a More and More Accurate Operational Wave Forecasting System: Thanks to Altimetry

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The recent events regarding to hurricanes IRMA and MARIA in the french west-indies showed the highest level of relevance of providing accurate analysis and forecast of the sea state. This need is directly related to elaborating waves submersion warning system and risk management for the safety of people and goods at the open oceans and coastal zones. The goal of this paper is to present a 10-year review of the assimilation of altimeters wave data in operational wave models of Meteo-France. Since 2008, regarding to JCOMM intercomparison the Meteo-France global wave system has been improved by more than 20% in terms of estimate of integrated analysed parameters of the sea state such as significant wave height. The model performance in the forecast period is assessed with the number of altimeters used in the operational system.

In this paper we examined the contribution of the altimeters data in the improvement of the operational wave system regarding to several aspects. Among these latter one can mention the wind forcing, the model physics and the waves/currents interactions.

A dedicated analysis for the impact of the assimilation of altimeters focusing on cyclonic seasons in the Indian and the atlantic oceans is highlighted. We investigated the improvement achieved on the timeliness of the best wave forecast. This point significantly eases the decision of warning level in case of dangerous event in seas. Further the improvement of extreme forecast index during the last 10 years will be discussed.

In the frame of perspectives we will address the relevance of using multi sources of satellite wave data for instance nadir and swath altimetry, and also the directional wave spectra provided by Sentinel-1 and the next CFOSAT mission. The review also opens the impact of the assimilation of altimeters on the ocean/waves coupling in the frame of Copernicus Marine service (CMEMS). Some promising examples will be highlighted and demonstrated. In the section of challenges for the future developments on the assimilation of high frequency altimeters wave data in coastal wave model will be discussed.

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Significant Wave Height in the Subpolar Seas of the Arctic: Monitoring Change over Two Decades with Satellite Radar Altimetry

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The surface waters of the Arctic Ocean and the marginal, subpolar seas freeze to form a seasonally-varying layer of sea ice, which can be centimeters to meters thick. The sea ice cover acts as a barrier between the ocean and atmosphere, attenuating ocean waves, particularly in the marginal ice zone. The mechanical impact of ocean waves on the sea ice cover remains poorly understood and is not well captured in climate and weather models. Satellite observations since the late 1970s reveal a diminishing ice pack in the Arctic Ocean, where ice extent is declining at a rate of approximately 4% per decade. The biggest changes are occurring in the sub-polar seas, and this is accompanied by an expanding marginal ice zone.

Since the 1990s satellite altimeters have provided daily measurements of sea surface height (SSH) and significant wave height (SWH) in the Arctic. In support of the NOAA/NASA Ocean Surface Topography Science Team (OSTST), our study assesses SWH just south of the ice edge, in the northern Atlantic and Pacific Oceans. We characterize the seasonal cycle, decadal trends, and inter-annual variability in SWH over a 22-year period, spanning 1996 to 2017. As sea ice extent in the Arctic has diminished, we investigate if wave heights have increased, and if these regions have become stormier. Using daily radar altimeter measurements from ERS-2, Envisat, Jason-1 and -2, CryoSat-2, and SARAL/AltiKa, we track and trend instances of large SWH in the Bering and Chukchi Seas, and in the Greenland-Norwegian-Barents Seas region. Our results indicate a small increasing trend in median SWH in both regions during the study period. In the northern North Atlantic, the occurrence of "very high" or "phenomenal" seas has tripled over the 20-yr period, while in the Bering Sea it has doubled. These trends towards stormier seas have potential impacts on coastal inundation in low-lying regions of the Arctic coastline. Our results also have important consequences for marine activities in the subpolar seas, such as fisheries and transportation.

We discuss additional statistical analyses to investigate the decadal trends, and the impact that an increasing number of daily observations has had during the study period. Next steps include applying a daily sea ice concentration mask to investigate the occurrence of waves within the marginal ice zone, and estimate SWH in these areas. We describe steps to disseminate our data products publicly through the NOAA CoastWatch/PolarWatch web portals. In anticipation of the launch of NASA's ICESat-2 mission in 2018, which will carry a laser altimeter, we also describe the generation of a monthly, average sea level anomaly to serve as a baseline against which to assess the absolute vertical accuracy of ICESat-2 SSH measurements in the Arctic and subpolar seas.

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Outreach, Education and Altimetric Data Services

ARGONAUTICA, an Educational Project Using JASON Data

De Staerke D.[1]

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The Argonautica educational project makes actual oceanographic data available to primary and secondary students. This satellite data makes it possible to understand the oceans, their relation to environmental change and the effects on the living world. It is a chance for them to undertake a real investigation by taking part in a scientific projects that alerts them to the evolutions in society and make them aware of the major challenges facing humanity and what is needed to protect the planet.

The Argonautica project, in relation to various events and/or with help from scientific partners, proposes the following activities:

- monitoring of drifting buoys, some of which are made by the classes, or Argos beacon. This will enable the students to understand oceanic circulation, the links between ocean and

environment (climate?) and how they vary, by comparing the data with that supplied by the JASON satellite.

- showing the impact of these variations on marine animals, by monitoring their migrations with Argos transmitters.

At the end of the school year, the students come together to report back on their work and two of the best projects have been chosen for a presentation at the OSTST Meeting.

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25 Years of Education and Public Outreach for Ocean Radar Altimetry at NASA/Jet Propulsion Laboratory

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Since the days of Topex/Poseidon, ocean satellite radar altimetry mission Education and Public Outreach (EPO) teams have made use of the satellite data and results, to inform educators and students, policy makers, data users, and the general public about the science, engineering, and societal benefits of accurately measuring sea surface height from space.

For over 25 years, our toolbox for conveying the value of these satellites has contained printed materials, CDs, public access websites, digital data, refereed literature databases, news media, public talks and activities, and hands-on activities.

The informational CD, "Perspectives on an Ocean Planet," answered questions such as, "what is the TOPEX/Poseidon mission? How does it work? And, what will it tell us about our ocean's role in climate? The highly-acclaimed educational CD, "A Visit to an Ocean Planet (VTOP)", targeted U.S. middle school students and provided classroom activities that enriched students' imagination and learning experiences in ocean science. The classroom activities were matrixed into the National Science Standards, and later became available online.

"Currents: The JPL TOPEX/Poseidon Newsletter" was an early, printed product, which included the latest mission science and engineering information, and was circulated throughout the science team community. The July 1997 special issue was devoted to a survey of the project's outreach activities all across the partner agencies.

Initially, outreach products and activities focused on TOPEX/Poseidon. The current strategy encompasses past, present and future ocean surface topography (OST) missions, to increase our leveraging capabilities.

The team joined with NASA's Space Place developers to produce, "Voyage on the High Seas," a board game to help middle school students understand global ocean circulation patterns. Teacher workshops helped educators make effective use of the board game in their classroom.

An original "El Niño Skit" is a fun way to get would-be thespians to understand, by acting it out, how a large El Niño can modify weather across the globe. While doing the skit, they learn how NASA and partners use radar altimetry to monitor the global ocean.

The NASA/JPL Sea Level From Space web site (sealevel.jpl.nasa.gov) includes pages for education: Junior oceanographer web pages; science data: El Niño Watch, Latest Jason data (updated bi-weekly); A searchable Literature Database of refereed literature; A Societal Benefits section; and Monthly features. The web site also includes partner data and links to partner sites.

Within the realm of EPO are media activities which include image releases, science stories, and thousands of stories carried in local-to-international media outlets. Local and national events and conferences benefit from OST missions within NASA Earth Science exhibits. Launch activities include Family and Friends events, science team meetings, and educator workshops. JPL public events including tours and the annual "Explore JPL" (formerly JPL Open House), which welcomes tens of thousands of people, would be incomplete without the important information brought to bear by 25 years of measuring the ocean from space.

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EUMETSAT Training in Ocean Remote Sensing

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EUMETSAT is responsible for delivering the Level-1 and Level-2 Sentinel-3 marine and lake products for Copernicus, and as such also plays a key role in promoting data to users and providing training opportunities. EUMETSAT Copernicus Marine and Ocean Training (CMOTS) programme is framed around participants working on their problems (problem-based learning), with tools for data access and manipulation provided to make this easy (scaffolding). Participants are required to create and share what they create (constructivist learning). The programme uses solely open access data and software, and is seeking to integrate with cloud-hosted processing to enable users in low bandwidth environments to overcome limitations in this respect. Beyond the courses the training programme also seeks to develop resources that can be used in training by others or for independent learning – such as instructional videos, code repositories, and Massive Open Online Courses.

The three sensors onboard Sentinel-3, including of course SRAL can be taught in the courses.

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The Evolution of Data Accessibility at PO.DAAC: Seasat to SWOT

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PO.DAAC has been distributing oceanographic data, including altimetry, since the early 80s by mailing tapes. Now PO.DAAC has terabytes of data accessible within seconds. This presentation will go into the history of data accessibility and technological advances through time and how it improved accessibility to altimetry data. PODS, the precursor to PO.DAAC, actually started because Seasat data had to be stored and distributed somehow. Distribution was done by mailing tapes. Then came CD-ROM, which provided more data density. While these methods made sure that the data were made available, the users were limited to experts as the discoverability and usability of the data were limited. By the time TOPEX/Poseidon launched data were available via ftp for download. With the Jason series data are available through many different platforms, which allows tools to be built to enhance accessibility. This now gives new ways of discovering data as you can query in space and time and visualize data without downloading it. The next big step will be SWOT, not just for the new technology of measuring water heights, but also in how the data will be made available. Due to the large data volumes SWOT data will be accessible on the cloud. While similarly functioning tools will still be made available new tools and methods need to be created to fully exploit the advantages of the new platform.

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Twenty Five Years of User Services for Altimetry Satellite Data: Aviso Experience and Lessons Learned

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For more than 25 years, Aviso has been Cnes altimetry mission user service. Set up in 1992 to process,archive and distribute data from the NASA/CNES ocean altimetry satellite Topex/Poseidon, the service has evolved to continue meeting the needs of the ever-increasing user community.

Its portal AVISO+ (www.aviso.altimetry.fr) is the entry point for 10000 registered users to freely access more than 40 products from CNES and CTOH not only for ocean-oriented applications but also for hydrology, coastal, ice applications.

In addition, the website proposes information on altimetry and DORIS to discover the techniques, the missions, the products and their use.

Challenges in the next years will be the dissemination of innovative data, the opening to new uses, the preparation for SWOT and CFOSAT

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Outlook #2: Sea State, Polar Oceans and New Techniques

CFOSAT mission, Towards the launch

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The Chinese and French Space Agencies are jointly preparing an innovative mission, CFOSAT (China France Oceanography Satellite project) devoted to the monitoring of the ocean surface and its related science and applications. The launch of CFOSAT satellite is expected for autumn 2018. The satellite is now in the final integration and test in DFH facilities (China).

The French wave scatterometer, SWIM, will be on-board CFOSAT. It will complete the Chinese wind scatterometer, SCAT. They will provide the scientific community with joint wind and wave measurements for the very first time.

SWIM is a Ku-band real-aperture radar with 6 rotating fan-beams pointing near nadir (0°, 2°, 4°, 6°, 8° and 10°). The main objective of this instrument is to provide directional wave spectra. The products delivered to users are:

- nadir measurements (significant wave height, wind speed),
- wave spectrum measurements,
- backscattering coefficient profiles from 0° to 10°.

The main characteristics of the SWIM instrument, the mission requirements and products are presented, as well as well as predicted performances estimated from simulations. An overview of Satellite Integration Campaign main results is given.

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The SKIM Mission for ESA Earth Explorer 9: a Pathfinder for Doppler Oceanography from Space

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The Surface KInematics Multiscale monitoring (SKIM) satellite mission is one of the two candidates under development for ESA Earth Explorer 9. The other candidate is the Far infrared Radiation Understanding and Monitoring (FORUM). Final selection will be done in 2019 for a launch in 2025. The ongoing work that is presented here aims at consolidating the mission objectives, instrument concept, and performance simulations.

SKIM uses a Ka-band Doppler radar that includes a nadir beam comparable to the altimeter on Sentinel 3, and off-nadir beams that will measure the surface velocity vector and ocean wave spectra across a 300 km swath. This should resolve surface currents and ice drift at spatial scales larger than a 40 km wavelength, with snapshots at least every day for latitudes 75 to 82, and every few days otherwise.

We present in particular the instrument principle, and an analysis of the SKIM error budget, including wave bias, platform attitude misknowledge and instrument noise. We also discuss the impact on the effective resolution of ocean surface currents in different regimes: equatorial currents, mid-latitude meso-scales, ice edge dynamics. SKIM should be able to measure processes that could not yet be observed directly from space, including near-inertial oscillations and divergences.

The proposed instrument can reveal features of tropical ocean and marginal ice zone dynamics that are inaccessible to other measurement systems, as well as a global monitoring of the ocean mesoscale that surpasses the capability of today's nadir altimeter constellation. The co-located wave measurements facilitates many applications. Beyond a primary focus of refining sea state biases in surface velocity and sea level estimates, wave data will be used for the investigation of wave-current interactions (including extreme sea states), wave-ice interactions and related feedbacks in the polar Marginal Ice Zones, air-sea fluxes including global carbon capture, or the analysis of transport and convergence of marine plastic debris and assessment of marine and coastal hazards.

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Development of a Potential Polar Ice and Snow Topography Mission

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On behalf of the study team this paper describes plans for developing a potential mission to continue and enhance observations of sea-ice thickness, land-ice elevation and oceanography parameters (SSH,SLA,etc.) to support operational and climate services.

The primary objectives of the proposed mission are:

1.Monitor critical climate signals: ice-sheet, ice-cap melting and sea level. In order to understand the contribution of the ice sheet and ice cap melting to global sea level rise and circulation, one needs to monitor mass balance of the major ice sheets and ice caps. Monitoring instabilities in the grounded ice sheet margins and floating ice shelves is also required to understand where and why mass loss is accelerated.

For ice sheets, glaciers/ice caps and permafrost regions, monitoring the surface elevation and its temporal change is required. The change of glacier mass over time (typically over annual intervals) is the basis for determining the mass-balance of the ice bodies and compiling the contributions to sea level rise. Precise, regularly updated DEMs are required as essential auxiliary data for deriving ice velocity maps from displacements in repeat-pass satellite imagery, for retrieving calving fluxes and ice discharge, for estimating iceberg freeboard, thickness and mass. In particular:

-High spatial resolution surface elevation (typically between 50 and 100 m sampling) and regular repeat observations for regions where major changes in surface elevation occur (typically ~5°), such as, outlet glaciers, boundaries of ice-sheets and caps, mountain glaciers, zones that are subject to permafrost erosion, icebergs.

-Low to moderate spatial resolution and an acquisition interval of a few months to get coverage: typically 1 km spacing, for low slope terrain (typically <0.2°) in the ice sheet interior, for example, Antarctica.

2.Monitor variability of Arctic and Southern Ocean sea-ice and snow-loading. The seasonal sea-ice cycles are hugely important for both human activities and biological habitats. Monitoring the inter-annual variability of sea-ice volume, extent and thickness not only offers one of the most sensitive climate signals, it is also essential for long term planning of any kind of activity in the Polar Regions. This requires an improved knowledge of snow loading on sea-ice. On shorter timescales, maps of sea ice thickness and types are essential to support increasing marine operations in those regions.

Secondary objectives are:

3.Support applications related to coastal/inland waters. Observation of water level at the (Arctic) coast as well as of rivers and lakes is a key quantity in hydrological research. Rivers and lakes not only supply freshwater for human use including agriculture but also maintain natural processes and ecosystems. The monitoring of global river discharge and its long-term trend contributes to the evaluation of global freshwater flux which is critical for understanding the mechanism of global climate change.

4. Contribute to the observation of ocean topography for global observation of mean sea level, mesoscale and sub-mesoscale currents, wind speed and significant wave height as a critical input to operational oceanography and marine forecasting services as well as ice thickness retrieval in the Arctic.

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A New Altimeter Concept for the Estimation of the Ocean Surface Directional Slopes

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Since the first altimeter, several improvements have been made in the electronics, in the signal processing or in the algorithms, but the operating principle remains the same. With the upcoming InSAR technique (SWOT mission to be launched in 2021), providing large swath altimetry data, the question of the evolution of altimeters arises. Swath altimeters will be more efficient for short time mesoscale products and conventional nadir altimeters will remain more suitable for low scale products because of their simplicity, their reliability and thanks to 25 years of accumulated experience.

Nadir altimeters provide the distance between the instrument and the mean sea surface under the satellite track. For oceanography, the main parameters extracted from this distance, after correcting it for instrument, atmospheric and geophysical perturbations, are the Sea Surface Height (SSH) above the reference ellipsoid and SLA (Sea Level Anomaly) after removing a Mean Sea Surface (MSS) from the SSH. The SLA is used to estimate time-variable sea level after reconstructing 2D gridded fields thanks to 1D profiles interpolation. If we consider the along-track data of a single altimeter, the cross-track resolution is as large as 300 km at the Equator which leads to limitations in this interpolation in the cross-track direction. Even using measurements of two or four satellites, these limitations are not fully resolved (Dibarboure et al. 2013). Consequently, a system providing slopes in the cross-track direction is of high interest. SLA has very low variations that are of the order of 1 meter over the world. Over areas of high currents as for the Gulf Stream, SLA can vary by 5 to 30 cm with slopes of up to 1 m over 100 km (0.001% or 5/6 m°). However, SLA variability can be much lower (of the order of 0.1 m°) (Morrow et al. 2003). In order to detect such low values of SLA slopes, it is then necessary to estimate SSH slopes with high precision of the order of 0.1 m°.

A new instrument concept inspired from ground radar tracking systems is proposed to measure the sea surface directional slopes in addition to the mean height. A study has been carried out in the R&D CNES program to evaluate the performance of this new concept. This evaluation has been performed by CLS with an end-to-end simulation tool representing the different stages of the measurement, starting from the generation of the physical scene (all kind of surfaces can be considered), the simulation of the orbit, the modelling of the on-board processing of the instrument and the geophysical retrieval algorithms.

Several configurations have been tested with a focus on the comparison between Ku and Ka frequency bands. It has been demonstrated that Ka band is of more interest than Ku band because of the possibility to use a higher PRF, and that Ka band configuration is able to estimate a slope as low as 1 arcsec for a spatial resolution of few tens of kilometers (few seconds of measurements).

In this presentation, we will provide a description of the new proposed concept, the methods used to estimate the directional surface slopes and the main performance results over ocean. We will also present comparison results with nadir altimeters in terms of height estimation performance.

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Radiometer for Coastal Altimetry

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Water vapour in the troposphere extends the satellite-to-surface round-trip time of satellite altimeter radars and is a significant factor in the overall altimetry error budget. Due to the spatial and temporal variability of water vapour, many satellite altimeters embark Microwave Radiometers (MWR) to concurrently measure and perform the so called Wet Tropospheric Correction (WTC) associated with water vapour.

ESA is currently having two parallel studies to define a new European radiometer instrument design that tackles the more challenging geophysical situations encountered in the coastal zones and inland water regions where strong gradients of atmospheric water vapour exist. This new radiometer is aiming at higher spatial resolution in order to improve coastal altimetry and also to cover other applications such as topography over sea ice, ice sheets and possibly also inland hydrology applications. This is achieved by embarking a set of high frequency channels to enable smaller antenna beam-widths and thereby more accurate WTC correction and altimetry in addition including the classical MWR channels for ensuring observation continuity. Such an instrument would be used by future operational altimetry missions.

The latest finding from the ESA studies will be presented including design aspects at system and equipment level, important trade-off aspects aimed at design optimisation and performance predictions.

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Plenary Closing Session Keynotes

SARAL/AltiKa: The Emblematic Ka-Band Altimetric Mission

Verron J.[1], Bonnefond P.[2], Aouf L.[3], Birol F.[4], Bhomwick S.[5], Calmant S.[4], Crétaux J.[4], Dibarboure G.[6], Dubey A.[5], Faugère Y.[7], Fleury S.[4], Gupta P.[5], Kumar R.[5], Morrow R.[4], Rémy E.[8], Rémy F.[4], Smith W.[9], Tounadre J.[10], Babu K.[5], Cancet M.[11], Chaudhary A.[5], Frappart F.[4], Haines B.[12], Laurain O.[13], Olivier A.[7], Poisson J.[7], Sharma R.[5], Thibaut P.[7], Watson C.[14]
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The India–France SARAL/AltiKa mission is the first Ka-band altimetric mission dedicated primarily to oceanography. The mission objectives were firstly the observation of the oceanic mesoscales but also global and regional sea level monitoring, including the coastal zone, data assimilation, and operational oceanography. SARAL/AltiKa proved also to be a great opportunity for inland waters applications, for observing ice sheet or icebergs, as well as for geodetic investigations. Launched on 25 February 2013, the mission ended its nominal phase after three years in orbit and began a new phase (drifting orbit) in July 2016; it has now already exceeded the 5-year time life. AltiKa data quality meets the expectations and initial mission requirements, and the characteristics of the altimeter and the Ka-band offer unique contributions in fields that were previously not fully foreseen. The objective of this presentation is to highlight some of the most remarkable achievements of the SARAL/AltiKa mission in terms of scientific applications. Compared to the standard Ku-band altimetry measurements, the Ka-band provides substantial improvements in terms of spatial resolution and data accuracy. We show here that this leads to remarkable advances in terms of observation of the mesoscale and coastal ocean, waves, river water levels, ice sheets, icebergs, fine scale bathymetry features as well as for the many related applications.

SARAL/AltiKa is in many respects a prototype of the altimetry of the future. SARAL/AltiKa represents the beginning of a new class of altimeters operating at Ka-band frequency with a small footprint and high pulse rate. The Ka-band is envisioned for several new altimetric satellite projects (i.e. AltiCryo from CNES, CryoSat-3 and SKIM from ESA) and the chosen band for SWOT. The extended capabilities that are offered by the Ka-band allow opening even more widely some new frontiers of altimetry such as coastal oceanography, cryosphere, and hydrology, beyond the traditional scope of the open ocean investigations.

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The Evolution and Status of Wide-Swath Altimetry

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Conventional altimeter constellations have been able to map two-dimensional ocean mesoscale sea surface height (SSH) at scales of roughly 100 km, but, due to limitations imposed by the number of satellites available, smaller mesoscales and submesoscale phenomena are not yet resolved. Conventional altimetry has also shown great promise in mapping water elevation for large surface water bodies, but does not have the spatial sampling or resolution to provide the coverage necessary to assess global water storage dynamics. Wide-Swath Altimetry uses radar interferometry at near-nadir incidence angles to provide high-resolution, high-accuracy two-dimensional water elevation measurements over swaths of 100 km to 200 km. Here, we review the science questions that require such measurements and their associated accuracy and spatial coverage characteristics. We then review the concept and historical development of wide-swath altimetry, and derive the measurement error budget for both ocean and surface water bodies. Finally, we show how these ideas have been matured in three mission concepts, culminating in the NASA/CNES Surface Water and Ocean Topography (SWOT) mission, scheduled for launch in the early 2020s.

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Achievements and Progress in Thales Alenia SpaceRadar Altimeters Product Line

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The last decade has seen the launch of several innovative radar altimetry missions. The Ku band SIRAL instrument of the ESA CryoSat mission and the Ka-band Alti-Ka altimeter of the CNES/ISRO SARAL mission have paved the way of a new era in altimetry, demonstrating improved technology and performances, in particular regarding range noise and spatial resolution over ocean and complex topography such as sea-ice, land-ice, inland waters, and coastal areas. The SAR and the SARIn techniques, as well as Ka band altimetry are now stepping into operational applications for Copernicus. Innovation is a continuous process and new high technology instruments are being studied and developed in Thales Alenia Space to further improve the performances of topography missions. The on-going development of the Poseidon-4 for the Jason-CS mission, the RF unit of the KaRIn radar for the SWOT mission, the preparation studies of the future swath altimeters for Copernicus NG, the preparation studies of the SKIM EE9 ESA mission are the new key challenges for technology to meet new sciences objectives.

The aim of the product line approach started in Thales Alenia Space in the early 2000’s with the support of CNES and ESA is twofold : to ensure data quality continuity to operational users with robust designs supported by high Technology Readiness Level and to propose technological innovations to open a new vision of our Planet. Thales Alenia Space designs and develops state of the art altimeters based on a building blocks approach of the product line and thanks to the continuous exchanges with the users community and the Agencies in order to build together the future radar concepts.

The paper presents a panorama of Thales Alenia Space achievements in radar altimetry over the last 10 years and the progress on the current developments. The preliminary results of future studies for swath altimetry beyond SWOT, the new radar concept for ocean waves and ocean current monitoring, the second generation design of AltiKa-SG for small class satellites for constellations will also be outlined showing the technology legacy and the commonality between the developments.

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Benefits of New Altimetry Techniques over Non-Ocean Surfaces: A Synthesis of CLS/CNES Recent Studies

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Over the last 25 years, a huge amount of data has been collected from space altimetry missions over the globe to get topographic measurements of both ocean and non-ocean surfaces. Recently, a new generation of altimeter satellites (Cryosat-2 in 2010, Saral/AltiKa in 2013 and Sentinel-3A in 2016) have proven their ability to provide value-added measurements over all surfaces (ocean, coastal, sea ice, ice sheets, inland water). They incorporated new instrumental features (e.g. SAR-mode altimeter for Cryosat-2 and Sentinel-3A, SARin-mode for Cryosat-2, Ka frequency for Saral) that have brought improved performances for retrieving geophysical parameters of interest like water level, sea ice freeboard or ice sheet elevation. Seven years after the first SAR-mode altimeter measurements and five years after the first Ka-band measurements, several analyses have been carried out at CLS/CNES allowing us to provide a comparison between all these datasets and to assess the relative performances of these missions.

Based on recent CLS/CNES studies, we propose to present a large review of the progress that has been made in radar altimetry since the advent of these new techniques, and to provide a comparison between them. We will also address their limitations with the ambitious objective to provide a clear understanding of the present altimetry missions complementarity, useful at the time of defining new observation missions and meeting new challenges.

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Poster Session

A Finer Understanding of the Processes Affecting Ocean Backscatter

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Sigma0, the normalized strength of the backscattered signal is often viewed as simply a by-product of altimeter retracking, yet it conveys a lot of information about the underlying surface and/or atmosphere. Over the oceans it yields a measure of the roughness viewed from directly overhead, providing complementary information to that obtained from obliquely-viewing scatterometers. Sigma0 has long been linked to wind speed, although it is clear that there are other factors contributing to the received signal. The advent of dual-frequency altimeters recording roughness at effectively different scales on the sea surface have helped demonstrate the variety of processes that may at times complicate the interpretation of sigma0.

Rain within the intervening atmospheric column has a marked effect, attenuating Ku-band and Ka-band signals, but only affecting around 5% of observations. Wave conditions have a subtle effect at low wind speeds, indicating how swell modulates the roughness spectrum, with changes dependent upon radar frequency. More recently the impact of sea surface temperature, through its effect on the dielectric content of sea-water has returned to prominence.

Sigma0 also has a role to play in cryospheric studies. Over sea-ice high backscatter values are associated with leads due to the near glassy water surfaces contained within them; over continental ice it provides some measure of the moisture content of the snow cap, especially when dual-frequency techniques can be exploited. Within the realm of land altimetry, large changes in sigma0 offer a good indicator of flooding beneath the tree canopy.

Over the past 25 years, there have been various changes in the defintion and precision of sigma0 records, with initial Topex measurements having a datation of 0.25 dB, whereas more recently efforts have been made to improve comparisons at the 0.05 dB level or better. In particular there have been issues about determining sigma0 using a waveform model incorporating mispointing, as there is significant cross-talk between the estimates of these two parameters. Such effects need to be fully understood and removed from climate records, else spurious trends in wind speed may result.

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Still Learning from ENVISAT 10-Year Altimetric Mission, 6 Years after Its End

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Usually planned for 3 to 5 years, altimetric missions often last longer. Envisat ESA mission launched in 2001 is a good example, with an altimeter life time of nearly ten years.

In 2012, ENVISAT mission was interrupted, but six years later, the mission’s historical database is still maintained, studied and used as a reference. After a first reprocessing (V2.1 in 2012), data were reprocessed once more to remain in line with the current altimetric missions such as AltiKa, Jason-2 and 3 or Sentinel 3.

Improved at several levels, the new data set includes a tenth of new standard fields enhanced for two types of reasons:

- thanks to a better understanding of some instrumental processing, learnt from studies performed on more recent missions (Altika, S3...). For instance, instrumental corrections, SWH look up tables, improved wet tropospheric correction.

- Or thanks to the geophysical corrections updates, enriched by a longer time series assimilation step of all the altimetric constellation. This is notably the case of MSS, tides or orbit solution...

Compared to the last reprocessing, the resulting data set benefit for several improvements and therefore, presents a much better capacity to describe mesoscale phenomena (improvement of error of Sea Surface Height (SSH) difference statistics at crossovers).

With a similar data availability, the homogeneity and performances are improved.

Level 2 production started in July 2017 and the whole dataset will be delivered to users after complete validation, in early 2018. It will ease the data merging for multi-mission altimetry, as it is essential for oceanography and applications.

This work gives an overview of Envisat dataset improving performances thanks to the various data processings. It illustrates the impacts on data at several scales: climate, mesoscales, coastal areas, high latitudes, focusing on major key steps, since 2001.

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The Copernicus Space Infrastructure: Status & Future

Jutz S.[1]

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The European Union (EU) led Copernicus programme is the world's largest civil Earth Observation (EO) programme and the biggest EO data supplier. It monitors Earth more accurate than ever before, and aims to give decision-makers across Europe useful information to act on, both at EU level and on a regional basis.

The Copernicus space component, coordinated by the European Space Agency (ESA), is composed of six families of dedicated satellites (the Sentinels) which work together to feed-back huge amounts of data on everything from land movement to ocean patterns, pollution to ice coverage, etc.

With six high-performance Sentinel satellites already in orbit, 9 other spacecraft still to be launched plus 5 instruments hosted on-board EUMETSAT satellites and more than 123.000 registered Sentinel data users on the ESA/EU Copernicus data portal, as well as numerous sophisticated operational services, the system has evolved at a breath-taking pace.

Access to data from these satellites and from other existing or planned missions is ensured through an integrated Ground Segment. All these data, along with measurements taken from Earth are used to fuel six thematic information services in the main environmental domains: marine, atmosphere, land, emergency, climate change and civil security.

The future evolution of the space component has already started with a large set of concrete needs and requirements gathered over the last 2 years. User and observation requirements have been identified, structured and prioritized in a continuous reflection process led by the European Commission (EC), and with the main support of ESA and other partners.

Two sets of requirements have emerged from different EC consultations and workshops, leading to the main elements of the future Space Component architecture:

- Expansion missions: enlargement of the present measurements through the introduction of new missions to answer emerging and urgent user requirements. These new observations would include, among others, CO_2 measurements to estimate anthropogenic emissions, high-resolution thermal observations, monitoring of sea ice and ice sheets in the polar region, hyper-spectral measurements and SAR L-band observations
- Next Generation missions: improvement of the current measurement capabilities, mostly by means of new generation of similar instrumentation compared to the ones currently deployed. They will ensure stability and continuity, while increasing the quantity and quality of products and services

Regarding the altimetry observations the Sentinel family currently contains two missions: Sentinel-3, a Synthetic Aperture Radar Altimeter from a sun-synchronous high inclination low orbit, and Sentinel-6, a radar altimeter from a non sun-synchronous mid-inclination high orbit, the latter in cooperation with the US. Enhanced continuity of these measurements shall be ensured in the evolution of the Copernicus space component.

This presentation will give an overview of the current status and future perspectives of the Copernicus space component.

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ESA Fundamental Climate Data Record for ALTimetry Project (FCDR4ALT)

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The ESA Fundamental Climate Data Record for ALTimetry (FCDR4ALT) project is part of the ESA Long Term Data Preservation Programme (LTDP) aimed at the preservation of ESA's assets in science data from space, which patently embraces the Earth Observation (EO) data. The ESA LTDP programme funds the data preservation, the data valorization and data accessibility of ESA & Third Party Missions (TPM) EO "Heritage Missions", starting 5 years after the end of the satellite nominal operations.

Following the successful decades of ERS and Envisat Altimetry mission operations and data exploitation, the FCDR4ALT project shall revisit the long-standing series of Altimetry observations (i.e. associated Level 1 & Level 2 processing, data set validation and traceability according to the QA4EO standards, provision of uncertainties, generation of FCDR time series and thematic data products, etc) with the objective of improving the performance of the ESA heritage data sets and their continuity with current (e.g. CryoSat, Sentinel-3, Jason) & future missions for multi-disciplinary applications and broader data use.

This paper aims at presenting the status of the ESA FCDR4ALT project, expected to be issued as an ESA Intention To Tender (ITT) in the second quarter of 2018.

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Polar Altimetry

Shepherd A.[1], Wingham D.[2], Muir A.[2], Ridout A.[2], Gilbert L.[2], McMillan M.[1], Tilling R.[1], Konrad H.[1], Slater T.[1], Otosaka I.[1], Hogg A.[1], Gourmelen N.[3]

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Satellite and airborne altimetry have transformed our capacity to study the polar regions, and the past 25 years of altimeter measurements have painted a new and unique picture of how Earth's ice sheets, ice shelves, sea ice, and polar oceans evolve. As global temperatures have risen, so too have rates of snowfall, ice melting, and sea level rise, and each of these changes impacts upon the neighbouring land, marine, and atmospheric environments. Altimeter measurements are now central to our awareness and understanding of Arctic and Antarctic environmental change. A case in point is the marine ice sheet instability that is underway in West Antarctica, widely understood to be among the greatest contemporary imbalances in the climate system, whose evolution has been charted in altimeter data since its onset.

This paper introduces a series of recent studies that have allowed both long-standing and unanticipated scientific problems in cryospheric research to be solved over the past five years. It also reports on the landmark studies in altimeter retrievals that underpin these discoveries. We discuss the techniques that have been developed to allow multi-decadal measurements of land ice, sea ice, and polar ocean elevation change, paying attention to new waveform re-tracking, interferometric processing, geophysical corrections, and approaches to time-series formation. This includes work on waveform deconvolution, and dual-frequency radar altimetry. We also present case studies on the use of these data to record multi-decadal trends in ice sheet mass balance, sea ice volume, and ocean circulation. Finally, we focus on a collection of very recent discoveries, including developing and utilising full swath-interferometric processing for mapping ice sheet elevation and elevation change, exploiting Altika and Sentinel-3 for land and sea ice studies in both hemispheres, tracking grounding line migration, verification of global sea level projections, partitioning snow and ice mass trends, and detecting the fingerprint of the seasonal melting cycle. In all cases, we explain how satellite and airborne altimetry have informed thinking across the wider scientific community.

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The Ocean Mean Dynamic Topography: 25 Years of Improvements

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Since the very beginning of altimetry, 25 years ago, the lack of an accurate geoid has hampered the direct use of altimeter signal for computing the ocean absolute dynamic topography and, hence, by geostrophy, the ocean surface currents. To cope with the uncertainty on the geoid, the so-called 'repeat-track' method has been developed and Sea Level Anomalies (SLA) are computed with centimetre accuracy. To correctly analyse the altimeter signal and assimilate it into operational forecasting systems, the full dynamical signal needs to be reconstructed from the SLA. Knowledge of the ocean Mean Dynamic Topography (MDT) is therefore required with both high accuracy and high resolution.

At large spatial scale, the MDT may be obtained by filtering the difference between an altimetric Mean Sea Surface and a geoid model. The filtering length is imposed by the geoid commission and omission error level. With the launch of dedicated space gravity missions as CHAMP (2000), GRACE (2004) and GOCE (2009) huge improvements have been made in the last 20 years for the estimation of the geoid. Recent satellite-only geoid models based on GRACE and GOCE data have centimetre accuracy at spatial scales down to around 100 km.

To compute higher resolution MDT, a number of methodologies have been developed. The geoid itself can be improved at short scales locally using in-situ gravimetric data or globally using the shortest scales information of the altimetric Mean Sea Surface. On the other hand, the large-scale MDT based on the satellite-only geoid models may be improved thanks to the use of in-situ oceanographic measurements (drifting buoy velocities, dynamic heights from hydrological profiles). Alternatively, the synthesis of all available information (in-situ oceanographic data, altimetry) can be done in a dynamically consistent way through inverse modeling or through data assimilation into ocean general circulation models, whose outputs are then averaged to obtain an estimate of the ocean Mean Dynamic Topography.

The aim of this talk is to give an overview of the huge improvements that have been achieved in the past 25 years for the estimation of the ocean Mean Dynamic Topography thanks to the launch of dedicated space gravimetry missions, the development of new computation methodologies, and the increasing number of oceanographic in-situ data. Perspectives will also be given in the upcoming context of high resolution wide-swath altimetry, and increasing need for high resolution coastal products.

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The Younger, Thinner, Faster Arctic Sea Ice Cover: Tracking Change Over Fifteen Years

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Satellite laser and radar altimeters observing the polar and subpolar seas now provide extensive monitoring of the sea ice cover, spanning two decades. We use these novel data to derive sea ice freeboard, thickness, and surface roughness, tracking changes in the inter-annual variability of Arctic Ocean sea ice over a fifteen-year period, between 2003 and 2017. High-resolution measurements from airborne laser and radar altimeters, and visible cameras operated during IceBridge surveys of the winter ice pack, are used to gain further insights of the deformation characteristics of the Arctic ice cover. In anticipation of the launch of NASA's ICESat-2 mission in 2018, we describe our recent work towards creating a synthesized time series of Arctic sea ice thickness, using measurements collected by ICESat, CryoSat-2 and IceBridge. This includes an improved tracking of the trends and variability in the first-year and multi-year sea ice thickness distributions. Combining altimeter measurements with satellite scatterometer observations from Metop-A/-B, and synthetic aperture radar (SAR) composites from Sentinel-1 A and B, provides new insights into the dynamic changes occurring in the Arctic sea ice cover today. By improving knowledge of the complex relationship between the ice cover and the polar climate system, our goal is to provide multi-sensor data products that advance capabilities to model and predict future change. We disseminate data products publicly through the NOAA Laboratory for Satellite Altimetry data catalogue and NOAA PolarWatch web portal.

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Twenty-Five Years of Progress in Sea Floor Mapping by Satellite Altimetry

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Although ships equipped with deep-water multi-beam echo-sounding (MBES) swath mapping systems and satellite (GPS) navigation have been around for the last 25 years, they rarely collect data in unexplored ocean areas. The most accurate and detailed sea floor sounding data are mostly confined to shallow coastal areas around developed countries, and a few deep-water areas that have been the focus of particular efforts (such as the search for the missing Malasia Airlines flight MH370 aircraft). Almost all the global ocean floor area lies more than a few hundred kilometers from the nearest GPS-navigated MBES data, and global ocean floor depth models must rely on older, low-tech single-wide-beam echo soundings recorded on analog scrolls and often positioned with only celestial navigation (most of the available data in the remote oceans was collected prior to 1965). If the ocean floor area is divided into squares one nautical mile (1.85 km) on a side, and all data, both GPS-MBES and old, low-tech data, are combined, only 8 percent of squares have any data at all. For this reason, global ocean floor mapping relies on satellite altimetry to guide the interpolation of gaps in unmapped areas.

The largest variations in sea surface topography are time-invariant and exhibit geoid height anomalies produced by the Earth's gravity field. At high wavenumber (full wavelengths approximately 10 to 160 km) these anomalies are usually correlated with sea floor topography, but can also arise from sub-seafloor tectonic structure buried beneath seafloor sediment. Resolving anomalies at this scale requires satellite altimeter profiles of sea surface height along a dense network of ground tracks, so that the inter-track spacing adequately samples scales as short as 5 km or less.

The first altimeter mission to yield a dense network of tracks was the European Space Agency's ERS-1 mission, completed in March of 1995. Marine gravity maps made from these data were exhibited at the Spring 1995 Americal Geophysical Union meeting, and this may have prompted the U.S. Navy to release the Geosat dense track data, collected in 1985-86 but classified Secret until July 1995. Some southern ocean Geosat data had been previously released in 1990 and 1992, allowing algorithm development for bathymetric estimation from dense track altimetry.

After the 1990s there was a long period with no new dense-track altimetry, and so seafloor mapping made incremental improvements as geodesists learned to improve the along-track resolution at high wavenumber using specialized retrackers and high-data-rate filters designed to extract the seafloor topography signal.

With CryoSat-2 in a long-repeat orbit since 2010, and the Jason-1, Jason-2, and SARAL/AltiKa missions also going into dense-track orbits at the end of their primary missions, there is now a rennaissance in seafloor mapping. Efforts are underway to see how many previously uncharted seamounts may be found, and how much resolution may be squeezed out of the newer mission data.

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The Contribution of Barotropic Processes to the Sea Level Variability in the Southern Ocean and to the Variability of the ACC Transport Across the Kerguelen Plateau at Interannual Time Scales.

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The barotropic response of the ocean is known to be a significant contribution to Sea Surface Height (SSH) variations at high latitudes. While we expect the barotropic signal to be larger at subseasonal timescales, it may not be negligible at longer timescales.

Here we examine the Southern Ocean's barotropic response to the wind at timescales ranging from seasonal to interannual, using simulations from a finite-element barotropic model, assessed against altimeter and GRACE observations. Simulations are in particular used to analyze the variability of the branch of Antarctic Circumpolar Current (ACC) that passes across the Kerguelen Plateau through the Fawn Trough, the transport of which was directly measured during 1 year from current meter data, a series subsequently extended to 20 years thanks to the Topex/Jason altimeter archive. We examine in particular the relevance of the so called 'Southern Mode' paradigm at such time scales to account for the observed variability.

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A Western Tropical Atlantic Circulation Analysis Using Statistics and Satellites

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The western tropical Atlantic ocean is a very energetic and highly variable region. It is one of the main contributors to the inter-hemispheric mass and heat transports. This study gives a new picture of the space and time variability of this region using statistical tools applied to satellite measurements such as radar altimeters (TOPEX/Poséïdon/Jason series...), Soil Moisture and Ocean Salinity (SMOS) radiometer, and the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) products. The investigated variables are thus the Sea Surface Temperature (SST), the Sea Level Anomalies (SLA) and the Sea Surface Salinity (SSS) between 70°W-20°E, 0°N-15°N, from 2010 to 2015. Using analytical methods from the statistical and machine learning field, like the Self-Organizing Map (SOM), it is possible to classify the different phenomena located in that area and to identify their characteristics. We will focus on the dynamics of the North Brazil Current, and the North Equatorial CounterCurrent, respectively, and their links with the InterTropical Convergence Zone and the Amazon river run off.

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25 Year Mesoscale Eddy Trajectory Atlas on AVISO

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A new "Mesoscale Eddy Trajectory Atlas" will be released in second semester 2018 on the Aviso altimetry portal. This dataset was produced and validated by CLS in collaboration with D. Chelton from Oregon State University.

This version of the eddy atlas will be produced from 25 years of new daily altimetry maps (DUACS/CMEMS-DT 2018) of SSH based on sampling by two satellites. The new dataset will introduce a new design to track eddies, which will allow missing detection on short time and also provide an extended dataset with shorter track than 28 days. In addition to the locations of the detected eddies along their trajectories, the atlas includes additional information about the amplitude, rotational speed, radius, eddy type (cyclonic/anticyclonic) and we will introduce a flag which store missing detection.

This poster will summarize the methodology and the improvements added in this new version of the eddy dataset, and will describe the associated assessment results, including the impacts with respect to previous releases.

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Assessing Gridded Hydrographic Observations against Satellite Data to Investigate the Southern Ocean's Mixed Layer Budget at Interannual Time Scales

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The Southern Ocean is a major ventilation window of the World Ocean, and a pivotal element of the meridional overturning circulation (MOC). There, isopycnals outcrop and upwelled waters are exposed to intense buoyancy forcing, to form intermediate and mode waters, as well as bottom water. The rate of formation and properties of these waters depend on exchanges with the atmosphere through ocean mixed-layer (ML) processes.

Profound changes have occurred in the past decades both in the southern hemisphere's atmospheric circulation, with and intensification of the winds, and in the water masses forming in the Southern Ocean. There is therefore a high motivation to analyze the ML variability at interannual time scales, its interplay with subsurface layers, and to gain insight into the dominant mechanisms driving its response.

A current limitation in the investigation of the ML heat budget at interannual time scales over the ice-free Southern Ocean is the ability to accurately estimate the

Mixed-Layer Depth (MLD), which stems from hydrographic observations. The space-time data coverage of hydrographic profiles has greatly improved in the historically undersampled Southern Ocean thanks to the advent of Argo floats. Still the scattered hydrographic data need to be mapped and it remains unclear whether the consideration of such fields in the Southern Ocean decrease the signal to noise ratio.

Prior to analyzing ML budgets, we assess the 'In Situ Analysis System (ISAS)' products distributed by the SNO Argo at LOPS in the Southern Ocean. ISAS (Gaillard et al 2016) was developed to produce gridded fields of temperature and salinity that preserve as much as possible the time and space sampling capabilities of the Argo network of profiling floats.

Because we lack independent information for the MLD, this assessment is instead carried out for the steric height which is compared to the Sea Surface Height (SSH) from the satellite altimetry archive (TOPEX/Poseidon-Jason). The barotropic variations the SSH needs to be corrected for at high latitude is obtained both from a model and satellite gravity data from the GRACE (Gravity Recovery and Climate Experiment) mission.

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A Comparison of Global Nonstationary Semidiurnal Internal Tidal Sea Surface Height Variance between Altimeter Observations and A High Resolution Global General Circulation Model.

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The fraction of nonstationary semidiurnal internal tide sea surface height (SSH) variance is compared between altimeter observations and a high-resolution global ocean model for the first time. The five years of modeled ocean output can be analyzed in the frequency-domain [Savage et al. 2017]. However, altimeter observations only sample particular locations once every several days, making frequency-domain estimates of this variance impossible. Therefore, wavenumber-domain techniques are typically applied to estimate non-stationary internal tide variance from altimetry [Zaron et al. 2017]. To gauge the skill of the wavenumber-domain techniques, an observing system simulation experiment (OSSE) is constructed in which the model is sampled at the locations and times that would be observed by the Topex/Poseidon altimeter if its mission had continued throug the timespan of the model run (2006 through 2010). The subsampled model output is then analyzed using the wavenumber-domain techniques and compared to the hourly-sampled frequency-domain "truth". Results are forthcoming, but it is expected that the multi-day temporal aliasing in the wavenumber-domain analysis is unable to differentiate between mesoscale and internal tidal variability and will therefore produce significant differences in the two variance estimates in regions with high mesoscale variability, such as in western boundary currents and the Antarctic Circumpolar Current.

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Spectral Signatures of the Tropical Pacific Dynamics from Model and Altimetry: A Focus on the Meso/Submesoscale Range

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The processes that could contribute to the flat Sea Surface Height (SSH) wavenumber spectral slopes observed in the tropics by satellite altimetry are examined in the tropical Pacific. To limit the impact of technical issues on the spectrum calculation, the taper window usually applied on altimetric data needs to be adjusted because of the energetic large scale motions, along with the segment lengths required to capture the broader mesoscale range. Based on a 1/12° global model, the tropical dynamics is investigated from spectral analysis to discuss on anisotropic signature, ageostrophic motions, kinetic energy flux with a special focus on the meso/submesoscale range. The equatorial region is dominated at every scales by anisotropic and ageostrophic motions. The spectral signature is dominated by the Tropical Instability Waves with a peak of energy at 1000 km, an inverse cascade of energy for scales larger than 500 km, and an inertial like forward cascade down from 500 km. The off-equatorial regions are characterized by a relatively narrow 100-250 km mesoscale range dominated by an inverse cascade of energy. Both regions have modeled surface power KE spectra consistent with 2D QG quasi-geostrophic and SQG turbulence that do not explain the observed altimetric spectra. Sea level does not respond to the ageostrophic equatorial dynamics, and the wavenumber SSH wavenumber spectra have low spectral power but maintain a steep slope consistent with quasi-geostropic turbulence. Based on 1/36° high-frequency regional simulations, with and without explicit tides, we find a strong signature of internal waves and internal tides in the western tropical Pacific that act to increase the smaller-scale SSH spectral energy power and flattening the SSH wavenumber spectra, in accordance with the altimetric spectra. Coherent M2 baroclinic tide is the dominant signal at ~ 140 km wavelength, but the shortest scales are dominated by incoherent internal tides which extend up to 200 km in wavelength, therefore impacting on alongtrack altimetric SSH today and on the future SWOT swath observations raising the question of SWOT observability at short scales in the tropics

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Evolution of Sea-Level Variability from Open Ocean to Coastal Zones in the South China Sea

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The South China Sea (SCS), located between the western Pacific and eastern Indian Ocean, is the largest semi-enclosed marginal sea in the northwest Pacific Ocean. Its bottom topography is characterized by two extended continental shelves with water depth less than 200 m along the north and southwest coasts and a deep basin with a maximum water depth of about 5000 m in the central region. Previous studies indicate that inter-annual sea-level variability in deep-water areas (water depth greater than 200 m) and its steric component are driven by El Niño-Southern Oscillation events, and the seasonal sea-level variability -- particularly the annual cycle in shallow water areas -- is largely dominated by the Asian monsoon. However, the link between open-ocean and coastal sea level variability at intra/inter-annual to decadal timescales relevant to climate is still unclear.

This aim of this work is to investigate how sea-level variability evolves from open ocean to coastal zones using more than two decades of satellite altimeter data complemented with long-term tide-gauge records to better understand the transmission of the oceanic signal across the shelf to the coast in the SCS. As linear trends derived from tide-gauge records in this region are contaminated by land-height changes of both natural and anthropogenic origins, in this work we focus on intra-annual sea-level changes that have an immediate impact on marine coastal systems. We explore the characteristics of both temporal and spatial variations in the intra-annual sea-level harmonics derived from tide-gauge and satellite-altimeter data, and develop regression models to understand the mechanisms driving the observed changes and the link between open-ocean and coastal sea-level variability.

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Patterns and Variability in Sea Surface Height: Linkages to Low Frequency Variability of North Atlantic Circulation

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The now 25-year record of satellite altimetry allows examination of decadal changes of ocean surface circulation and heat content. Here, we present analysis of sea surface height using a new method for identifying low frequency modes of variability, called low frequency component analysis (LFCA). LFCA identifies spatial patterns (low-frequency patterns, LFPs) that have the maximum ratio of low-frequency to total variance, allowing isolation of low-frequency variability. Here, the LFPs are constructed to be linear combinations of the first 30 empirical orthogonal functions of sea surface height (SSH). The first low frequency mode of SSH variability (low-frequency component, LFC 1) shows an overall increase in SSH over the basin, reflecting an increase of heat content throughout the basin. The exception of this increase can be found in the Irminger Sea where only small changes in SSH occur. In addition, the SSH height difference across the Gulf Stream downstream of the New England Sea Mounts is found to be decreasing over time, indicating a trend towards a weaker Gulf Stream. LFC 2 reflects the low frequency response of SSH to changes in the North Atlantic Oscillation. LFC 3 suggests an increase in Gulf Stream or Northward shift of the North Atlantic current coincident with a decrease in the strength of Irminger Sea surface geostrophic circulation. Analysis of SST (sea surface temperature) using the same method shows different patterns of variability that have much larger spatial scales, suggesting that changes in SST are controlled both by ocean circulation changes and by large scale atmospheric forcing while changes in SSH mostly reflect changes in ocean circulation.

We also employ LFCA in analysis of SSH from a control (constant radiative forcing from greenhouse gases) coupled climate model (HadGEM2-ES) and find similar patterns of variability as found in the observations with some distinct differences. Model LFC 1 is similar to observed LFC 3, however changes in the subpolar gyre model LFC 1 are more concentrated in the Labrador Sea than in the Irminger Sea. In addition, the model LFC 1 suggests an expansion of the subpolar gyre to the south with little change in the Gulf Stream strength. The model LFC 1 leads subpolar North Atlantic SST by two to three years suggesting that changes in subpolar gyre circulation lead to changes in SST. This indicates an active role of ocean circulation in low-frequency temperature variability of the North Atlantic and that SSH could be used as a predictor of that temperature variability.

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Altimetric Analyses of Oceanographic Pathways during El Niño Events: Connections between the Equator and West Coasts of North and South America

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We analyze the 25-year altimeter sea level anomaly (SLA) fields to describe the oceanographic pathway connecting the west coasts of North and South America to the ENSO variability in the eastern equatorial Pacific Ocean. During the altimeter record, the major (warm) El Niño episodes that can be compared are found during 1997-98 and 2015-16, with moderate events in 2002-03 and 2009-10. The 2014-16 period included a 'marginal' El Niño in 2014 prior to the major event the following year. Although the 2014-15 anomalies in circulation did not develop into a full El Niño, they provided an extended period of poleward transport next to Central America and Mexico that set the stage for larger final poleward displacements by the end of the 2015-16 El Niño off North America. The net effects of similar poleward transports along South America will be compared to the North American counterpart. Most analyses of these events use SST anomalies in specific equatorial regions (usually some distance to the west of South America) as the primary indicator of El Niño strength, which is appropriate for analysis of the atmospheric pathway between the tropics and mid-latitudes. Correlations between mid-latitude signals and Equatorial indexes are used to make the connection. Along the oceanographic pathway, however, the signal can be followed, making SLA next to the coast of South America the more appropriate index for analysis of the poleward spread of the equatorial ENSO signals into both hemispheres during the warm events. SLA is also a more dynamic signal than SST, serving as a proxy for anomalies of both integrated heat content and pycnocline depth. It is also less easily disguised by surface processes such as cooling due to high winds, as found next to gaps in the mountains next to Central America. Along the U.S. West Coast we use a blend of altimeter and tide gauge heights to capture the height and geostrophic velocity signal more realistically and with higher resolution within the 50 km next to the coast.

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Extracting Periodic Signals of the Sea Level Variations and Their Relation to Climate Indices Around Australia

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This study aims at investigating and extracting the periodic signals of the sea level using 25 years of altimetry data around Australia. The sea level trend is then determined by a parametric model including the detected periodic signals. Unlike other studies, this parametric model is merely based on the detected interdecadal and decadal signals from altimetry data. The detected signals in sea level variations can also be seen in the estimated power spectra of the climate indices in the study area. In addition to annual signal, the periods of 1.5, 3, 4.13, 5.7 and 11.17 years demonstrate distinct peaks in the power spectra of the sea level and climate indices, which have all passed the significance test with a 95% of confidence level. The determined trends in the area show a good agreement with studies that consider effects of climate indices through a multivariate regression function. Moreover, the model in this study presents more descriptive explanation of the sea level variation around Australia in terms of periodicity and spatial variability.

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Assessment of Annual Sea Level Budget since 2005

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The global mean sea level is an important indicator for changes in the climate system in response to natural as well forced (natural and anthropogenic) climate variability. The temporal evolution of sea level helps in detecting changes in sea level components and sea level budget analysis helps in constraining missing components. Here we present our study on annual sea level budget analysis over 2005-2015 using individual sea level components as well GRACE data for mass components. We find that while the annual sea level budget is closed until 2011 within the range of associated uncertainties, there is a consistent underestimation from sum of sea level components since 2012. We discuss possible sources of non closure of the sea level budget, and successively examine different potential candidates such as deep ocean warming (below 2000m) and steric contribution from the Arctic and southern regions. Furthermore, lack of GRACE data over several months since 2012 is also being considered to examine the source of underestimation.

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Numerical Modelling of Non-Tidal Ocean Dynamics for the Reduction of Spatio-Temporal Aliasing in Global Grids of Sea-Level Anomalies From Radar Altimetry

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Global grids of sea-level changes derived from altimetry data accumulated over several days are increasingly popular in many applications of both marine research and environmental monitoring. High-frequency variations in sea surface height at periods below twice the averaging period are, however, prone to cause aliasing artefacts in the grids in line with the Nyquist theorem. Such artefacts degrade the quality of the gridded products and potentially result in misleading geophysical interpretations. Since many years, the so-called dynamic atmospheric correction (DAC) based on a global barotropic ocean model is used for this purpose.

In this study, we utilize surface height variations from the ocean general circulation model MPIOM to correct the altimeter data for high-frequency ocean signals. MPIOM is taylored to predict non-tidal perturbations in satellite orbits (AOD1B RL06; Dobslaw et al., 2017). The data extends back to the launch of the GEOSAT mission in 1985 and is routinely updated into present time. Tidal signatures associated with effects of atmospheric tides were carefully removed in order to retain the non-tidal variability only. For our analysis, we have access to 3 hourly global grids of sea surface height anomalies separated into its barotropic and baroclinic components.

Based on data from different satellite missions (Topex, Jason-1, Saral-Altika) for selected years, we will demonstrate that applying model-based corrections to along-track data substantially reduces the high frequency variability of the gridded sea-level anomalies. Whereas modelled density-related sea-level changes turn out to be less effective, we find that removal of barotropic signals caused by time-variable surface wind stresses and atmospheric pressure variations significantly reduces high-frequency variability in global gridded products. The effect of this correction step is in particular visible in areas of strong wind-driven ocean dynamics as the Southern Ocean and the North Atlantic.

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Complementing Satellite Altimeter Measurements with AIS Data to more Precisely Monitor the Aghulas Current

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The Agulhas Current is one of the strongest western boundary current in the world's oceans. It plays a significant role for the Indo-Atlantic inter-ocean exchange and global thermohaline circulation (Lutjeharms, 2006). Using in-situ current meter measurements Bryden et al. (2005) calculated the average poleward volume transport of the Agulhas Current (from 5 March-27 November 1995) to be about 70 +/- 22 Sv (1 Sv = 106 m3 s-1). More recently, a trend in Agulhas Current transport has been estimated using 3 years of in situ measurements combined with coincident along-track satellite altimeter data spanning the years 1993–2015 (Beal and Elipot, 2016). To note, satellite radar-detected Doppler shift measurements have been reported to confirm the expected intense and persistent manifestation of the Agulhas Current, reaching, at time, larger than 2 m/s surface currents.

Here, we report on new unambiguous estimation of ocean surface velocity using the increasing data set from the Automated Identification System (AIS), initially used to monitor vessels trafic. Here applied to the year 2016, ocean surface current estimates from AIS data are demonstrated quantitatively complement altimeter estimates, especially the gridded altimetric products from Aviso. As understood, gridded altimetric producs inherently suffer from an insufficient spatio-temporal sampling. Moreover, within the core of very strong currents, the majority of in-situ drifting buoys are often rapidly expelled, and extreme surface currents may largely be under-estimated.

AIS data provide the speed and the course with respect to the ground, together with the true heading of the ship. In the Agulhas region, more than 150 ships per day can be selected, over the 1000 available fleet. Combining the AIS information with the a priori direction of the current vector given by the altimetry, the surface velocity magnitude is estimated, and then compared to altimetric gridded products, but also individual altimeter track estimates. As systematically found, higher AIS-derived velocities are generally obtained. The resulting AIS daily gridded product is build at 0.1 degree resolution. As more precisely mapped, the continental shelf is shown to strongly steer the current in the North-East part, up to approximately 25.5°E. Beyond this mark, entering the Agulhas Bank, the current displays a stronger variability, to evolve into a less energetic and more meandering flow towards the retroflection region, centered at 38-39°S, 18°E.

As daily sampled, analysis and correlation are reported to better illustrate links with changes in sea surface temperature. Moreover, the intermittent behavior of the current is also shown to depend upon local wind changes. In view of the need to establish a more comprehensive monitoring system for the greater Agulhas Current, these first results invite to consider the AIS data for routine quantitative monitoring of heat and mass transports in this region.

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Satellite Altimeter Combined Measurements and Local Persistent Small-Scale Ocean-Atmosphere Signatures

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Strong ocean currents can modify the height and shape of ocean waves, possibly causing extreme sea states in particular conditions. The risk of extreme waves is a known hazard in the shipping routes crossing some of the main current systems. Modeling surface current interactions in standard wave numerical models is an active area of research that benefits from the increased availability and accuracy of satellite observations. Indeed, satellite altimetry is quite unique to provide contemporary measurements of three main variables of the ocean / atmosphere interface, i.e the sea surface height, the significant wave height, and the mean square slope. However, at scales less than 100 km, where meso and sub-meso scale turbulence takes a significant part in the variability of the ocean/atmosphere coupled system, standard along-track (1Hz) measurements are impacted by different sources of noise, instrumental and geophysical, and possible numerical sampling issues. It causes a blurring of the mesoscale and submesoscale geophysical variability induced by ocean-atmosphere interactions.

To analyse such short scale variability, we report a typical case of a swell system propagating in the Agulhas current, using wind and sea state measurements from several satellites, jointly with state of art analytical and numerical modeling of wave/current interactions. Further, to generalize, we then report a statistical analysis in this scale range using an empirical mode decomposition for 2015 as year of reference, and data from Jason-2, Cryosat-2, and Saral altimeters. Accordingly, the geophysical co-variance of the three variables at these short scales can then be more robustly analysed, especially to reveal and interpret persistent small-scale ocean-atmosphere features.

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Global Wavenumber Spectra from SARAL/Altika and Sentinel-3 Observations

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The wavenumber spectra of along-track Sea Surface Height from the altimeter missions SARAL/Altika and Sentinel-3 are analyzed. Saral is in conventional "low-resolution mode" but with low noise levels and improved signal-to-noise. Sentinel-3 is in SAR mode. The use of the spectral shape to interpret the surface eddy regime at global scale is revisited with these two missions. Wavelength range for the spectral slope estimations is determined as a function of local first-baroclinic Rossby radius of deformation (Lr) and the Rhines scale (LR). The wavelength range varies spatially, rather than the fixed wavelength range of previous studies. Results show that spectral slope is generally steeper than k^{-3} (where k is the wavenumber) in the extra-tropics (reaching slope values steeper than k^{-4} in high energy eddy regions), and flattens towards the equator (values around k^{-2}). Processing steps of careful editing and corrections, noise removal, and spectral segment lengths can impact on these spectral slope estimates. The 1-Hz noise shape is different in LRM Saral data and SAR Sentinel-3 data and needs adapted processing. The higher signal-to-noise ratio of these missions reveals an important seasonality of the spectral slope values, with an overall flatter spectrum during the winter months in comparison to summer (slope variations are in the order of 0.5 to 1.5 from one season to the other). Analysis of the error levels also exhibit seasonal variations, which suggests a non-negligible contribution of the local sea-state and dynamical regime to the noise levels.

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Ocean Meso Scale in the Copernicus Marine Environment Monitoring Service Global Ocean Eddy-Resolving Physical Analysis, Forecasting and Reanalysis

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Over the past years, Mercator Ocean has been regularly upgrading its global ocean physical reanalysis through improvements in the ocean model, assimilation scheme and assimilated data sets. The last upgrade concerned the eddy-permitting reanalysis GLORYS2V4 (¼° horizontal resolution and 75 vertical levels) covering the altimetry era (1993-2016). R&D activities have been conducted at Mercator Ocean in 2016/2017 in order to propose, in the framework of Copernicus Marine Environment Monitoring Service (CMEMS), an eddy-resolving physical reanalysis called GLORYS12V1, covering the same time period and based on the current real-time global forecasting CMEMS system (1/12° horizontal resolution and 50 vertical levels).

In parallel to the operational system, a twin free-numerical simulation (without any assimilation) has been performed on the period 2007-2015. The model component is the NEMO platform driven at the surface by ECMWF ERA-Interim for the reanalysis and operational IFS analysis for the real time. Observations are assimilated by means of a reduced-order Kalman filter. Along track altimeter data (Sea Level Anomaly – SLA), satellite Sea Surface Temperature (SST), Sea Ice Concentration and in situ temperature and salinity (T/S) vertical profiles are jointly assimilated. Moreover, a 3D-VAR scheme provides a correction for the slowly-evolving large-scale biases in temperature and salinity.

This presentation will provide an overall assessment of this first global 1/12° ocean reanalysis highlighting the level of performance and the reliability of this new eddy-resolving physical reanalysis. Specific focus will be on the representation of meso scale features at global scale and associated eddy kinetic energy at the surface but also at depth. Impact of the model resolution and of the data assimilation of altimetric observations will be detailed based on diagnostics as comparison with observations and eddy characteristics in the reanalysis.

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ACC Circulation and its Variability in the Udintsev Fracture Zone from Altimetry and in Situ Observations

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The Udintsev Fracture Zone (UFZ) constitutes the strongest chock point of the Antarctic Circumpolar Current (ACC), where the circumpolar flow is most narrowly channeled through a series of deeply-cut faults formed by spreading of the South Pacific mid-ocean ridge. The mean dynamic topography from altimetry shows clearly the tight concentration of three major ACC fronts within a limited latitudinal width of 200 km, with the Polar Front passing through the UFZ and the Subantarctic Front through the Eltanin Fracture Zone, consistent with previous frontal studies from hydrography. Recent studies emphasized the utmost importance of the ACC chock points for the cross-stream transport of heat and momentum, which is known to play a primary role in the meridional overturning circulation of the Southern Ocean, although in situ observations quantifying these features are very limited. We have made recently two lines of CTD sections during the deployment and recovery cruises of current meter moorings across the UFZ in February 2016 and December 2017, respectively. We present here the preliminary results of frontal circulation and volume transport from the in situ data, in comparison with those from altimetry and an operational model from MERCATOR. Special emphasis will be paid on the eddy statistics from altimetry for diagnosing the eddy-mean flow interaction and accessing the geographical location and intensity of the cross-stream ageostrophic flow, an essential ingredient of the Southern Ocean overturning circulation.

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High Resolution Tidal Modelling at Regional Scales

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With amplitudes ranging from a few centimetres to several meters in some continental shelf regions, the oceanic tide is a large contributor to the ocean topography variability observed by satellite altimeters, and more particularly in the shelf areas. In most scientific applications using altimetry data, global models are used to remove the tidal signals from the altimeter sea surface heights in order to focus on other ocean dynamics signals. The accuracy of these tidal models is generally at the centimetre level in the open ocean. The main error sources of the models are located on the shelves, where the tidal signal is amplified and more difficult to comprehend because of complex and often not well-documented bathymetry, combined with strongly non-linear tidal interactions.

Better knowledge of the tides improves the quality of the altimeter sea surface heights and of all derived products, such as the altimetry-derived geostrophic currents, the mean sea surface, the mean dynamic topography, the bathymetry and the geoid. It is also of particular interest when comparing altimetry and tide gauge sea surface heights in the framework of CALVAL activities. In addition, accurate tidal models provide highly strategic information for ever-growing maritime and industrial activities in the coastal regions.

The increase in grid resolution, together combined with local model tuning, is one of the means to improve the tidal model performance in coastal regions and large improvements have been achieved thanks to this approach. However, tidal models are very sensitive to the bathymetry accuracy on the shelves, where the ocean tides show the largest amplitudes and are strongly non-linear. Increasing the resolution of the model grid implies consistent bathymetry quality and accuracy, which is today the main limiting factor to high resolution tidal modelling. Various sources of bathymetry data exist but many regions remain not well-known because of too sparse measurements, data access limitation or large temporal variability of the seabed dynamics.

With new and future altimetry missions reaching ever more coastal areas and resolving the ocean dynamics at ever finer scales, the need for high resolution accurate tidal model solutions is more challenging than ever.

This presentation aims at highlighting some recent and on-going work on high resolution tidal modelling at different scales (from global to local), including new efforts to improve the bathymetry in some coastal regions.

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Surface Film Thickness from Ku/C Band Backscatter Relation

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Most altimeters operates at dual frequencies, Ku (13.5GHz) and C (5.3GHz) band. The relationship between the two band backscatter that has been used in the past to detect the samples affected by rain samples using the differential attenuation of the signals by liquid water, contains a wealth of information on the surface roughness at different wavelengths and their relationships to sea surface parameters such as wind, surface films or surface currents.

The analysis of Jason-1 and -2 and Envisat data during the Deepwater Horizon oil spill and the comparison with oil spill thickness and extent data provided by Environmental Response Management Application (ERMA) showed that oil spills distort the altimeter waveforms and can cause 'blooms' in the radar backscatter cross-section signal

The comparison of high resolution surface sigma0 obtained by waveform inversion method and ERMA oil cover fields allowed to quantify the impact of oil spill as a function of wind speed and oil thickness. A further analysis showed that surface films have a differential impact at Ku and C band depending on the existing surface roughness (due to wind) and film thickness. This differential impact reflects in the Ku-C band relationship by modifying the departure from the "normal" Ku-C band relation. The analysis of the modification of the Ku-C band backscatter difference by surface film of different thicknesses and the comparison to the relationship for low winds cases and surface films show that the departure from a "normal" Ku-C band relation can be used to detect the presence of surface film.

The Jason2 and Jason-3 archives have thus been processed to analyze the sigmabloom events. In a first step, all the bloom events (whatever their length) of sigma0 larger than 16dB are detected and their characteristics (occurrence, geographical distribution, length, strength, wind speed) analyzed. In a second step, the departure from the Ku-C band relationship within the bloom is analyzed to give a tentative estimate of the presence of surface films.

The impact of surface currents (in particular the Aghullas Current) is also analyzed to show the impact of surface current on the KU/C band relation.

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Sea Level and Ocean Heat Content Variations of the Antarctic Continental Shelf

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Sea level and ocean bottom pressure on Antarctica's entire continental shelf fluctuate near-uniformly in a circumpolar manner. The intra-seasonal to inter-annual fluctuations are barotropic and are driven by winds along the continental slope. Whereas the ocean's dynamic sea level and ocean bottom pressure responses are spatially near-uniform, the wind's contribution varies geographically owing to regional differences in bathymetry. The circumpolar sea level fluctuation is accompanied by temperature and heat content changes that can affect ocean-ice sheet interaction and thus sea level rise. Unlike sea level, however, ocean heat content changes are regionally confined. The circumpolar sea level fluctuation provides a proxy for integrated ocean heat content changes over the shelf that are otherwise difficult to measure.

The nature of these variations is examined using satellite observations and in situ measurements in conjunction with the latest ocean state estimate from the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO), ECCO Version 4 release 3. The ECCO state estimate provides an effective description of the three-dimensional time-evolving ocean state while its adjoint affords a means to quantitatively investigate causal mechanisms of ocean circulation.

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Interannual Variability of Mesoscale Eddy Kinetic Energy in the Indian and Pacific Oceans

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Mesoscale eddies play an important role in meridional transports of heat, freshwater, and nutrients. Interannual and decadal changes in eddy activity have implications for the temporal variability of the large-scale circulation, as well as the distribution of biological productivity in the global oceans. Moreover, this study found a positive correlation between sea level variations and mesoscale eddy activity in many areas of the oceans; hence we seek to identify the mechanism(s) that explain the apparent relationship of sea level and mesoscale motions in these areas.

In this study, the sea level anomalies (SLA) from merged satellite altimeter data are decomposed into large-scale and mesoscale components, in order to separate the variability specific to mesoscale motions from longer planetary waves in the Indian and Pacific oceans. We first focus on a band of elevated mesoscale eddy activity in the subtropical southern Indian Ocean (SSIO), between Madagascar and Australia. In the eastern SSIO region, where mesoscale eddy kinetic energy (EKE) variability is positively correlated with sea level variations, remote forcing from the Pacific is the dominant influence. A higher sea level in the western tropical Pacific during La Niña conditions drives downwelling coastal Kelvin waves and a stronger Leeuwin Current, increasing the generation of mesoscale eddies that radiate towards the west. The Pacific also contains numerous regions where the positive SLA-mesoscale EKE correlation is observed. EKE variations just west of Mexico and Peru are induced by wind forcing of coastal waves propagating poleward, with some influence from ENSO. In the northern subpolar gyre of the Pacific, we examine the role of wind forcing and wind energy input in producing the positive SLA-mesoscale EKE correlation. The contributions of sea level variability and wind forcing, as well as interior pathways of EKE propagation, supplement our traditional understanding of mechanisms of eddy generation and present new ways to assess ocean variability using the multi-decadal altimetry record.

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Diagnosing the Drivers of Regional Decadal Sea Level Change with ECCO

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The twenty-five-year record of sea surface height (SSH) from satellite altimetry has revolutionized our ability to observe the temporal and spatial structure of decadal sea level variability. There is a continued need, however, to understand the forcing and mechanisms that give rise to the decadal changes. Only with increased dynamical understanding can we distinguish between anthropogenic and internal variability and develop predictability to aid in coastal planning. Over the last 10 years, the family of data-constrained ocean state estimates from the Estimating the Climate and Circulation of the Ocean (ECCO) consortium have been instrumental in elucidating the drivers of decadal sea level change. These experiments not only reproduce the observed SSH variability to good approximation, but they have the particular advantage of producing solutions that obey conservation laws exactly and are free of artificial sources or sinks of heat, momentum, freshwater, etc. This latter characteristic makes it possible to create closed heat and salt budgets that are useful for diagnosing the relative contributions of advection, diffusion, and surface-flux forcing to regional steric sea level variability. When applied to a suite of forcing experiments in which components of the forcing are set to climatology, the result is a powerful tool for isolating the dynamical links between surface forcing and sea level response. Here, we provide an overview of progress made and ongoing work toward applying these techniques in ECCO state estimates for the purpose of understanding mechanisms of observed decadal sea level change in the altimeter record. Applications include wind-driven decadal variability in the North Indian Ocean, the effect of horizontal gyre circulation on trend reversals in the Subpolar North Atlantic, the importance of diabatic thermodynamic processes for decadal SSH variability in the tropical Pacific, and global hemispheric asymmetry in the long-term rate of sea level rise.

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How Does Resolution and Data Assimilation Affect the Predictability of Internal Tides in a Global Ocean Circulation Model?

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Tidal internal waves (internal tides) are relevant for ocean mixing processes and their sea-surface-height signature may convolute the extraction of non-tidal motions from altimetry signals. Global ocean models can provide insight in the generation, propagation, and dissipation of low-mode internal tides. Improving the internal tide predictability in these models contributes to a better understanding of these mixing processes and allows for a better separation of the tidal from the non-tidal motions in satellite altimetry. In this talk, I will present simulations of global HYCOM, the operational forecast model of the U.S. Navy. The simulations have 41 layers and are forced with tides and atmospheric fluxes and stresses. I will compare tidal sea-surface height variance and energy balances of simulations with a horizontal resolution of 8 and 4 km and with and without data assimilation (DA) of the background flow. I will demonstrate that the 4-km simulations contain more internal tide energy than the 8-km simulations. A fraction of this increase can be attributed to a better resolution of higher vertical modes in the 4-km simulations. The increase can also be attributed to a decrease in the amplitude of the linear wave-drag term, which regulates the damping of both the surface and internal tides. This implies that a separate damping term may be needed for the surface and internal tides in higher resolution simulations. Interestingly, the simulations with DA have more realistic energy levels when compared to altimetry, which may be attributed to a more realistic stratification. Finally, I will show that in the higher resolution simulations the non-stationarity of the internal tide increases by 15-20%. The mechanisms of this increase will be explored.

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25 years of Monitoring the Antarctic Circumpolar Current at Drake Passage

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The Antarctic Circumpolar Current (ACC) is an essential component of the global climate system connecting the major ocean basins as it flows eastward around Antarctica.

The Drake project took place from 2006 to 2009 and consisted in several hydrographic cruises and in a mooring array deployed along the track #104 of Jason satellite. Satellite altimetric data are in good agreement with in situ observations ([1], [2], [3], [4], [5], [6], [7]) and document basin circulations and eddy activity in Drake Passage.

A 20-year-long volume transport time series of the ACC through the Drake Passage is estimated from the combination of information from in situ current meter data (2006–2009) and satellite altimetry data (1992–2012) ([8]). A new method, look-up table method, for transport estimates had to be designed. It accounts for the dependence of the vertical velocity structure on surface velocity and latitude. The mean cross-track surface geostrophic velocities are estimated using an iterative error/correction scheme to the mean velocities deduced from 2 different products of mean dynamic topography. The full-depth volume transport has a mean of 141 Sv and a standard deviation of 13 Sv. Full-depth transports and transports over 3000 m barely differ as in that particular region of Drake Passage the deep recirculations in two semi-closed basins have a close to zero net transport.

The volume transport is then analyzed to better understand the ACC transport variability and its potential causes ([9]). The time series of three transport components (total (TT), barotropic (BT), and baroclinic (BC)) referenced to 3000 m present energetic intraseasonal fluctuations. Low-frequency variations are much less energetic with a significant variance limited to the annual and biannual timescales and show a nonstationary intermittent link with the Southern Annular Mode and the Nino 3.4 index for interannual timescales. The local BT (and TT) variations are associated with a well-defined tripole pattern in altimetric sea level anomaly (SLA). The tripole pattern associated with BT is generated locally (BT basin mode) when the BC-associated tripole results from mesoscale SLAs that have propagated eastward from an upstream area of Drake Passage.

On the occasion of this symposium on the "25 years of Progress in Radar Altimetry", we updated the transport time series to obtain a 25-year volume transport time series (1992-2017) of the ACC in Drake Passage. This updated volume transport time series is compared to volume transport from the 1/12° global ocean reanalysis from Mercator Ocean.

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25 Years of Malvinas Current Volume Transport at its Northernmost Extension: Variability and Drivers

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The Malvinas Current (MC), the northward flowing western boundary current of the Southwestern Atlantic Ocean is an offshoot of the Antarctic Circumpolar Current and extends up to 38°S. Currentmeter mooring data in the northernmost extension of MC have been obtained at 41°S at three opportunities: in 1993-1995 (contribution to WOCE project, [1]), 2001-2003 (contribution to CLIVAR project, [2]) and 2014-2015 (CASSIS Malvinas project). For each period, velocities derived from satellite altimetry data are highly correlated (> 0.8) with 20-day low-pass filtered in-situ velocities from current meters deployed at 300 m depth [3]. Gridded data are preferred to along-track data [3]. Combining satellite altimetry and the in situ data sets from the three 10-years apart mooring deployments, a 24-year long volume transport time series of the MC at 41°S was produced [4] using a look-up table method [5] . Three types of shear were used to estimate the uncertainty attached to the lack of information on the velocity shear in the upper 300 m of the water column [5]. The accurate look-up table method provides a re-evaluation of the mean transport with respect to previous estimates performed using a classic method [6, 2]. On the occasion of the "25 years of Progress in Radar Altimetry" Symposium, we updated the transport time series (1993-2017).

The drivers of the MC transport variations at 41°S examined in [7] were revisited [5, 8]. Transport extrema at 41°S are not driven by upstream conditions on the slope. Instead, transport maxima appear to be related with cyclonic eddies detached from the Polar Front which propagate northward above the 4000 m isobath up to 41°S. Transport minima are due to positive anomalies shed by the Brazil Current overshoot that manage to move westward onto the slope. Altimetry and Argo floats show that at times, the MC is cut from its source downstream of Drake Passage by anticyclonic anomalies propagating westward along the Malvinas Escarpment at 48°S [8]. These blocking events are recurrent and last about a month. However, they do not seem to affect the MC flow at 41°S, as a cyclonic recirculation cell is established between 38°S and 48°S, with the MC being its western boundary. The Malvinas Plateau restricts the northward penetration of mesoscale activity. Consequently, variations of sea level anomalies south of 53°S do not impact the MC further north.

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A Regional Analysis of the West Tropical Atlantic Ocean Variability

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The west tropical Atlantic Ocean is a western boundary circulation system and the place of inter hemispheric connections of the global circulation in the Atlantic Ocean. The southern and central branches of the South Equatorial Current feed North and South Brazil currents systems, and the seasonal equatorial recirculations, that exports heat and salt in the rest of the Atlantic ocean. The interannual and seasonal ocean variability is impacting the regional climate variation, with some extreme drought and rainfall over the South American continent. The PIRATA Atlantic Mooring network, sea cruises and experiments, and the regional observing system along Brazilian coast allow to describe water masses variability. In complement, we provide the description of the mesoscale feature and variability in the area, using along track satellite altimetric data since 1993. In particular, some prominent turbulent features associated with the bifurcation of the southern South Equatorial Current and their variability are described here from in situ and satellite observations. However, using the recent release of L3 along-track satellite altimetric data from the CMEMS we infer the reliability, over time of this altimetric dataset for regional scales tropical studies. This study is a preliminary work in the frame of a proposal for a SWOT Brazil initiative dedicated to the Tropical Atlantic fine scales descriptions.

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Near-Real Time and a 25-Year Reanalysis of Global Ocean Currents at the Surface and 15m Depth from the Synergetic Use of Altimetry, GOCE, Wind and In-Situ Data.

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Accurate estimate of ocean surface currents is both a challenging issue and a growing end-users requirement. Advancing the quantitative estimation of ocean surface currents from satellite sensor synergy and demonstrating the impact in user-led scientific, operational and commercial applications was the main objective of the GlobCurrent project, a Data User Element (DUE) from the European Space Agency (ESA). In the framework of this study, a global reanalysis of 25 years (1993-2018) of global ocean currents at two depths (surface and 15m) has been calculated which is now distributed through the CMEMS (Copernicus Marine and Environment Monitoring Services) MULTI OSERVATION (MULTIOBS) Thematic Assembly Center (TAC). Also a Near Real Time production has been implemented and daily global maps of ocean currents at the surface and at 15m depth are also available via CMEMS. The currents are estimated as the sum of the geostrophic and Ekman components. The geostrophic component is based on the SSALTO-DUACS multimission altimeter maps of velocity and the CNES-CLS13 Mean Dynamic Topography, both distributed through the CMEMS Sea Level TAC. Ekman currents at two levels (surface and 15m) are calculated from an empirical model. The model parameters (amplitude and angle) have been derived as to minimize the misfit between wind stress data and the ageostrophic component extracted from in-situ drifter velocities (SVP drifters at 15m depth, Argo floats at the surface). Parameters have been fitted by month, longitude and latitude. They feature a clear seasonal cycle in good agreement with the ocean stratification. Also, the surface and 15m Ekman currents show a spiral-like response to wind stress in good qualitative agreement with the theory. Currents have been calculated over a 25 years period (1993-2018) and an estimate of the current accuracy is provided together with the current values. Finally, preliminary results will be presented from on-going studies aiming at further improving the Ekman model and the Mean Dynamic Topography components.

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On the Relative Information Content of Surface Data versus Interior Data in Constraining the Large-Scale Ocean Circulation and Its Variability

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Satellite altimeter data, along with sea surface temperature, sea surface colour, and to a lesser extent sea surface salinity, are routinely combined with interior source of data such as ARGO to produce ocean state estimates. The relative importance of surface data versus interior data in constraining the large-scale ocean circulation and its variability is in practice dependent on the data assimilation scheme used to produce ocean state estimates, however, and remains theoretically poorly understood. In this work, a theoretical understanding of the issue is sought from the viewpoint of a high-resolution (1/12 degree) NEMO simulation taken as truth, and focuses in a first step on the information contained in sea surface height for the purpose of reconstructing interior velocities. A traditional viewpoint is adopted, which consists in projecting the surface information on vertical modes. First, the regional complexity of the ocean is explored using standard EOF analysis, which identifies the regions of the ocean that are in principle easier to reconstruct, such as the ACC or western boundary currents, the equatorial regions appearing the more complex ones. Second, the issue is investigated of how many vertical modes can be isolated for different time scales. The second part of the work will discuss some of the fundamental issues associated with the analysis of the thermodynamic part of the signal, most notably the problem of decomposing temperature and salinity into passive and active anomalies, based on the introduction of a new physically-based neutral density variable and new definition of spiciness.

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Sea Level in the Mediterranean and Black Seas: the Regional Imprints of Large-Scale Atmospheric and Oceanic Dynamics

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Due to the effect of atmospheric and oceanic dynamics, sea level at the regional and local scales can be substantially different from the global mean sea level change. The densely populated coasts and large infrastructure in low-lying delta regions of the Mediterranean and Black Seas are particularly vulnerable to sea level extremes. Satellite altimetry observations over the last quarter-century have shown that the regional non-seasonal (seasonal cycle removed) sea level extremes can reach amplitudes of a few tens of centimeters. Here, we present some new aspects of our mechanistic understanding of sea level variability in the Mediterranean and Black Seas that resulted from an Ocean Surface Topography Science Team project entitled “The Mediterranean and Black Seas: Analysis of Large Sea Level Anomalies”.

The project was motivated by the Mediterranean mean sea level rising more than 10 cm above the average monthly climatological values in the boreal winter months of 2009/2010 and 2010/2011. The non-seasonal anomalies were observed in sea surface height (from altimetry), as well as in ocean mass (from gravimetry), indicating that they were mostly of barotropic nature. Based on satellite observations and atmospheric reanalysis data, the non-seasonal sea level and ocean mass fluctuations in the Mediterranean Sea were attributed to concurrent wind stress anomalies over the adjacent subtropical Northeast Atlantic Ocean, just west of the Strait of Gibraltar, and extending into the strait itself. These wind stress anomalies, modulated by the North Atlantic Oscillation pattern, can directly impact the sea level gradient between the two ends of the strait and lead to nearly simultaneous basin-wide changes of sea level in the Mediterranean. In the northeast, the Mediterranean Sea is connected to the semi-enclosed Black Sea via the shallow and narrow straits of Bosphorus and Dardanelles. Although freshwater balance is an important driver for the sea level variability in the Black Sea, we have revealed that the Black Sea level also responds to sea level changes in the Mediterranean, and lags behind them by 10-40 days due to friction and geometry of Bosphorus. The Mediterranean and Black Seas are an integral part of the North Atlantic climate system, and interestingly, observations show that basin-wide variations of sea level in the Mediterranean Sea are negatively correlated with the Atlantic Meridional Overturning Circulation (AMOC) northward transport at 26°N: a stronger/weaker AMOC is associated with a lower/higher sea level. In particular, the aforementioned extreme sea level anomalies in the Mediterranean coincided with the AMOC slowdown in 2009/2010 and then again in winter 2010/2011. We show that this relationship is due to (i) the direct effect of wind forcing on both the Mediterranean Sea level and the AMOC, and (ii) the indirect effect of the AMOC changes through influencing the thermal structure near the eastern boundary of the North Atlantic Ocean.

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High-Wavenumber Variability in the Eastern Tropical Pacific from ADCP and Altimetry

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Recent studies have shown that inertia-gravity waves (IGWs) contribute significantly to oceanic variability at spatial scales smaller than 20-100 km, while geostrophic flows govern variability at larger scales. Model results suggest that the length scale of the transition from IGWs to geostrophic flow varies regionally. Shipboard Acoustic Doppler Current Profiler (ADCP) lines can be useful for evaluating this transition, but have been geographically limited. A concentrated effort to recover previously unprocessed ADCP transits from the eastern tropical Pacific has expanded the volume and geographic range of available data records. We compute one-dimensional wavenumber spectra and decompose them into rotational and divergent components (roughly proportional to vortex and wave components). We compare results with high-resolution model output from the MITgcm and with high-resolution along-track nadir altimetry (e.g. Jason data processed with the Adaptive Leading Edge Subwaveform (ALES) retracker). In the tropics, we find that the transition between from rotational to divergent spectra occurs at scales greater than 100 km. These scales are longer than transition scales identified in previously studied mid-latitude regimes such as the California Current or Drake Passage.

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Quantifying Atlantic Water Transport to the Nordic Seas by Combined Use of Gravimetry and Altimetry

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In this study the variability of Atlantic Water (AW) entering the Nordic Seas from the North Atlantic through the passage between Iceland, the Faroe Islands and Scotland has been investigated. The poleward transport of this warm AW is a key component in maintaining a relatively mild climate in the northwestern Europe. Satellite remote sensing datasets from altimetry and the Gravity field and steady state Ocean Circulation Explorer (GOCE) mission, in combination with surface drifters, fixed current meter, and hydrographic data are used. The high-resolution mean dynamic topography (MDT) is shown to resolve the time-invariant surface currents in the inflow region. In addition to the improved MDT, we take benefit of the new reprocessed sea level anomaly data in the estimation of absolute dynamic topography. Analysis of the monthly surface velocities from 1993-2016 demonstrates significant influence of the large scale atmospheric forcing associated with the North Atlantic Oscillation (NAO). Furthermore, a significant increase in surface velocities along the slope current, front current and the Norwegian Coastal Current are found during winter. Finally, combining altimetry with hydrographic data, we demonstrate that the variability in surface velocities of the inflow region is also reflected in the deeper layers, and that altimetry therefore can be used to monitor the variability of the poleward transport of AW in this region.

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Advances in Studies of Upper Ocean Mesoscale Processes and Dynamics from Satellite Sensor Synergy: The GlobCurrent Findings

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Under ideal imaging conditions (no clouds, weak to moderate winds, etc) essentially all optical and microwave spaceborne sensors manifest presence of ocean fronts such as related to gradients and changes in: (i) infrared- and microwave radiometer-based sea surface temperature; (ii) imaging spectrometer-based chlorophyll distribution and concentration; (iii) altimeter-based sea level anomaly; (iv) Scatterometer and SAR-based surface roughness and (vi) SAR-based range Doppler shift. A common driver for the expression of these frontal boundaries is the surface currents and their spatial changes, involving meandering pattern and eddy formation. In particular, surface current changes and gradients related to shear, vorticity and strain invoke rotation, divergence and convergence with corresponding upwelling and downwelling in the upper ocean. Stability changes and corresponding local wind field adjustment in the atmospheric boundary layer is also commonly associated with intense surface current boundaries. Altogether these distinct changes establish gradients of sea surface temperature, sea level anomaly and sea surface roughness. Satellite sensor synergy is therefore offering advances in the routine monitoring of the two-dimensional surface expression of mesoscale upper ocean processes and dynamics. In this presentation we demonstrate this for meanders and eddies in the greater Agulhas Current regime. Jointly with coincident in-situ observations, it evidently creates an important step toward advances in near real-time monitoring and quantitative interpretation of mesoscale upper ocean processes and dynamics. As such, it also becomes highly valuable for numerical ocean model validation.

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How Can SWOT Better Reconstruct Horizontal and Vertical Velocities?

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The approach of this poster is based on the use of Observing System Simulation Experiments (OSSEs) of SWOT data together with conventional altimeters and in-situ observations (e.g. Argo) using a 1/12° regional model of the Iberian Biscay region that includes tidal forcing. The “true ocean” is a regional very high (1/36°) resolution model of the same Biscay area. Previous analysis of these experiments conducted in Benkiran et al. (2016) have shown a great improvement (when using SWOT-like data rather than conventional altimeters) of the root-mean-squared-error (rmse) of the Sea Surface Height (SSH) calculated with respect to the true ocean. This poster further explores these results including the analysis of the horizontal and vertical velocities fields and their vertical structure. Preliminary analysis shows that SWOT data allows a better positioning of eddies on frontal zone and thus a better control of the horizontal and vertical velocities.

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From Past and Present Nadir Altimetry Constellations to the SWOT Era: What is the True Effective Resolution of Altimetry?

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The DUACS system produces, as part of the CNES/SALP project and the Copernicus Marine Environment and Monitoring Service, high level multimission altimetry Sea Level gridded maps. Their effective resolution, kwown as about 180km wavelength overall, would actually feature strong regional variations, spanning from 120km in some high-latitude regions to more than 400km in the tropics. A detailed assessment of the effective resolution based on a cross-spectral analysis with independent altimetry profiles will be presented. In a second part, we will review some perspectives for improving the resolution in the context of future missions. The main challenge to face with new techniques is the lack of high temporal revisits, since shorter spatial scales cohabit with high-frequency processes such as internal waves. Although internal waves will obviously limit the time-space mapping capabilities whatever the spatial resolution of future altimeters, there is certainly some room for improvements by using future altimetry with optimal account of high-frequency processes and advective properties of balanced eddies.

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Assessment of Mesoscale Resolution Capability of Sentinel 3 and SARAL Altimeters with Respect to Kilometric-Scale Ocean Simulations.

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The increase in mesoscale resolution capability of present generation altimeters is expected to further improve our understanding of the contribution of mesoscale processes onto ocean circulation, and to allow for a more reliable assessment of the ability of high-resolution ocean models to resolve these processes. In this context, the recent availability of data from submesoscale-permitting numerical simulations provides a very valuable source of information. Besides, recent studies, based on altimetry and numerical simulations, have highlighted the strong seasonality of the mesoscale activity at mid-latitudes as well as a pronounced spatial inhomogeneity at the basin scale. Therefore, assessing the mesoscale resolution capability of recent altimeter data; how it varies in space and time and how it relates to submesoscale permitting simulations, are questions that need to be addressed. In this study, the seasonal wavenumber power spectral density of SSH obtained from SARAL (KA band) and Sentinel 3 (delay-Doppler SAR mode) is calculated over a set of fourteen 10°×10° boxes spread over the North Atlantic and compared to that of the hourly SSH of a 1/60° resolution simulation with NEMO NATL60. For the model, both the SSH interpolated along the relevant satellite tracks (1D, subsampled) and the SSH over the whole box (2D, full resolution) are considered in our spectral comparison. Our spectral analysis shows that altimeter data agree well with synthetic data extracted from the model for wavelengths larger than the instrumental resolution capability. The results suggest that the typical resolution capability of the two altimeters is comparable and ranges from 70 up to 90 km (wavelength). Spectra of both the model and altimeter data confirm the substantial seasonality of (sub-)mesoscale activity in the North Atlantic. Moreover, our results show that the two approaches, based either on along-track-sampled (1D) or 2D model data yield very similar estimates of SSH wavenumber power spectra (energy level and slopes). Finally, our study suggests that carefully tuned submesoscale-permitting ocean circulation model simulations have the potential to become a powerful ally to extrapolate (below resolution capability scales)and interpret existing altimetry data and to prepare future altimeter missions (as for instance the upcoming SWOT mission).

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AMOC from Space: The Importance of Synergy of Satellite and In Situ Measurements

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Satellite (altimetry and winds) and in situ (XBTs, Argo floats) measurements are used to estimate the meridional overturning circulation (MOC) and meridional heat transport (MHT) in the South Atlantic since 1993 in the region between 20°S and 35°S. Analysis of the 24-year time series of MOC and MHT indicates that the interannual variations in the MOC at different latitudes are statistically correlated, with MOC at 35°S leading that at 20°S by about 20 months. Results also show that the dominance of the geostrophic (density-driven) and Ekman (wind-driven) transports on the interannual variations in the MOC and MHT varies with time and latitude. The time series indicate that at 20°S the Ekman component plays a larger role than the density-driven component. On the other hand, at 35°S the geostrophic component dominates over most of study period, except during 2007-2012 when the Ekman component dominates. Further analysis shows that, consistent with results in other regions, the oceanic heat convergence drives the heat content changes in the study region on interannual time scale, which in turn forces heat fluxes into the atmosphere. The MHT at both 20°S and 35°S contribute to the oceanic heat transport convergence in the region, with MHT at the southern boundary (35°S) plays a slightly larger role. It is also interesting that both the directly wind-forced Ekman transport and density-driven geostrophic transport are important for total heat transport convergence, although the geostrophic transport contributes more than half of the variance in the oceanic heat convergence. This MOC induced heat convergence in the South Atlantic could act as a predictor for global extreme weather events, such as global monsoons.

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Mesoscale Eddies in Australian-Antarctic Basin Based on Altimetry Data

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We studied mesoscale eddies, identified with automated eddy identification procedure in the Australian-Antarctic basin for April, 8 1994. We studied and analyzed main physical characteristics of eddies: amplitude, rotation speed, translocation speed, lifetime, and radius. The advective nonlinearity parameter was calculated for each eddy separately. For each tracked eddy we calculated its trajectory from the moment of eddy origin until it disappears from the map of sea level anomalies. The calculated empirical estimates for the observed vortices were compared with the theoretical estimates obtained from the linear theory. It was demonstrated that nonlinear effects play a key role in the mesoscale sea level variability in the studied region. At the same time, for some eddies, the β effect has significant influence on the vortex dynamics in the region.

Key words: altimetry, SLA, sea level, mesoscale eddies, Rossby waves, Southern Ocean, Indian Ocean, sea level anomalies

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An Improved Satellite Altimetry Data Processing Dedicated to Coastal Areas: Validation over Algerian Coast

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The coastal zone is the unique part of the Earth where land, sea, air and people meet. By its nature it is a complex system where all the processes that influence its functioning are interconnected.

In coastal systems, shorter spatial and temporal scales make ocean dynamics particularly complex, so the coastal domain represents a challenging target for processing of satellite altimetry data.

The main objectives of this paper are to improve the altimetric measurement in coastal areas by analyzing the main problems related to atmospheric corrections that must be applied to this measurement to obtain a precise surface height.

The processing of Saral/Altika Geophysical Data Records with in-house developed algorithms, including: re-tracking which is important for the last 7 km next to the coast; a more accurate wet troposphere correction (decontaminated correction) and better modeling of atmospheric effects permit us to determination the sea surface height over the Algerian coast.

The obtained surface was validated with the in-situ tide gauge data, and found in good agreement.

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ALES Retracking Results for Sentinel-3A PLRM and SARAL/Altika Missions

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Standard processing of satellite altimetry, which is based on Brown-like waveforms, usually produces unreliable data in the coastal area due to a number of factors including interference from land and calm water in the altimeter footprint. This means that a reasonable amount of potentially valuable data are flagged as unusable.

The Adaptive Leading-Edge Subwaveform (ALES) retracker, originally developed at the National Oceanography Centre (NOC) Southampton (Passaro et al. 2014), is capable of retrieving data in coastal areas by avoiding echoes from bright targets in the trailing edge portion of the waveform. ALES also maintains the processing accuracy in the coastal area and the open ocean by adapting the width of the estimation window based on significant wave height (SWH).

This retracker has the potential to retrack all the pulse-limited altimetry missions and has already been successfully applied and validated at NOC for Jason-1, Jason-2, Envisat and more recently Jason-3 missions. Now this is being extended to encompass SARAL/Altika, which is the first Ka altimetric mission devoted to oceanographic studies, and Sentinel-3's pseudo-LRM mode emulated from the SAR mode using the reduced SAR mode techniques.

The NOC version of ALES underwent some adaptation to retrack the 40-Hz SARAL/AltiKa and the 20-Hz PLRM Sentinel-3A data. The relationship between the SWH and the width of the retracking window (which is a defining feature of ALES) has been estimated for these two cases using Monte Carlo simulations as for the original ALES algorithm. The new algorithm coefficients have been used to fit the waveform from the SGDR data products.

Here we present samples of our outputs of the ALES processing chain for both missions and their validations against tide gauge observations.

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Satellite Altimetry and Coastal Predictions of Atmosphere, Ocean and Wind Waves

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Experiments with atmospheric, ocean circulation and wind wave models in coupled and uncoupled mode help quantify the individual and combined effects of two-way coupling. The research is performed in dynamically complicated coastal ocean area, the southern part of the North Sea. The focus on the processes in the German Bight, which is a well-known tidally dominated region. In the first discussed experiment, amosphere and ocean waves are coupled by implementing wave-induced drag in the atmospheric model. The two-way coupling leads to a reduction of both surface wind speeds and simulated wave heights. The research demonstrates the usefulness of altimeter data for validation and calibration of models. The coupled approach proved to be particularly important under severe storm conditions in the German Bight, which is a very shallow and dynamically complex coastal area.

In the second experiment the focus is on the impact of wind, waves, tidal forcing and baroclinicity on the sea level during extreme storm events. The effects of wind waves on sea level variability are studied accounting for wave-dependent stress, wave-breaking parameterization and wave-induced effects on vertical mixing. Again using altimeter data made possible to demonstrate that the coupled model has a better skill compared to the stand-alone circulation model. The wave-dependent approach yields a contribution of more than 30% in some coastal areas during extreme storm events. The contribution of a fully three-dimensional model compared with a two-dimensional barotropic model showed up to 20% differences in the water level of the coastal areas of the German Bight during storm Xaver in December 2013.

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Greenlandic Coastal Sea Ice Freeboard and Thickness From CryoSat-2 SARIn Data

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Coastal altimetry is becoming increasingly important and relevant to society in connection to sea level rise, fishery, shipping and other off-shore activities (Pugh and Woodworth, 2014). On the other hand, altimetry in coastal areas has proven to be more challenging than over open ocean due to e.g. land footprint contamination and degradation of geophysical corrections (Cipollini et al., 2010; Saraceno et al., 2008; Gomez-Enri et al., 2010).

In the last 8 years, ESA's CryoSat-2 (CS2) radar altimetry mission has made a big contribution to coastal altimetry. In fact, it enabled to measure sea surface height closer to the coast than conventional altimeters previously did, using SAR and SAR Interferometric (SARIn) acquisition modes to reduce footprint contamination.

This study builds on previous work by Abulaitijiang et al., (2015) and Di Bella et al., (in review) and attempts to estimate sea ice freeboard and thickness using level 1b SARIn data acquired by CS2 along the Western and Northern coasts of Greenland. The challenges and limitations of SARIn altimetry in coastal areas will be identified with the support of airborne and in-situ validation data from the CryoVEx and Operation IceBridge campaigns.

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Assessment of Ionosphere TEC Determination From Dual-Frequency Altimetry Missions With Reference to Local and Global GNSS-TEC Models in Coastal Regions

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Several satellites are nowadays equipped with dual-frequency altimeters that scan theoretically the whole ionosphere in the nadir direction. The two frequencies enable determination of ionospheric delay and thus total electron content (TEC) below the satellite orbit. This information helps in altimetry range determination, however is limited to sea/ocean areas. Therefore, global ionospheric models become a source of ionospheric corrections over lands and on the contrary, altimetry-derived TEC is an important source of validation for GNSS TEC models over the oceans, where the number of GNSS stations is limited. This study applies high-resolution regional GNSS-TEC model determined by least-squares collocation (LSC) and also lower-resolution global GNSS TEC models to the determination of ionospheric corrections for Ku-band, along coastal altimetry satellite track.

The GNSS-TEC values are then compared with altimetry-derived TEC over selected coastal region. The reason of this choice is that the observations from both techniques mostly overlap in coastal regions, due to the larger number of GNSS stations in the continental areas. On the other hand, coastal zones are investigated separately in altimetry, also due to the difficulties in the atmospheric corrections, e.g. dual -frequency ionospheric correction, which can be affected by the land in the altimeter footprint. The above reasons encourage to perform detailed study of ionosphere modeling in the coastal zone. Therefore, available altimetry-derived TEC determinations from Jason-2, Jason-3 and Sentinel-3A satellites have been assessed together with regional GNSS TEC model, determined with high resolution by least-squares technique-LSC. Global GNSS TEC models, modeled usually by lower order spherical harmonics with low resolution are additional background in the study. The study aims at systematic and random error analysis and enhancement of altimetry-derived TEC and ionospheric correction.

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The Low-Frequency Variability of the Agulhas Bank Circulation

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The ESA Sentinel satellite family missions are dedicated to the needs of the Copernicus programme. The proposed Glider-AirCore proposal results – once established – in high resolution vertical profiles of trace gases and auxiliary data and is therefore naturally linked to the ESA Sentinel 5P as well as the Sentinel 4 missions focusing on column integrated trace gas retrievals and weather observation data with high spatial resolution. The Glider-AirCore consists of a robust light-weighted glider carrying a long (> 100 meters) surface coated metal tube to sample air during autonomous descending in a spiral after its lift up to stratospheric heights by a balloon. Onboard instrumentations includes GPS tracker for navigation and wind retrievals, conventional humidity, temperature, pressure sensors, pyranometer (short-waves sun radiation) and pyrgeometer (long-wave thermal radiation) both up- and downward oriented. A CRDS spectrometer will be hooked up after landing of the Glider-AirCore to determine trace gas concentrations of $CO2$, CO, $CH4$ and $H2O$ with highest precision in the sub-ppm or sub-ppb range.

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Cross-Calibration of Retracked Jason-2 and Sentinel-3A SAR Sea Surface Heights AroundAustralia

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A Brown-peaky (BP) retracker has been developed and used to retrack coastal altimeter waveforms. In this paper, the performances of Jason-2 retracked 1 Hz sea level anomaly (SLA) dataset is assessed through a cross-calibration with Sentienel-3A synthetic aperture radar (SAR) dataset. The Jason-2 dataset is derived by reprocessing waveforms using the BP retracker, while the Sentinel-3A SAR dataset is provided by the Radar Altimeter Database System (RADS). Both SLA datasets cover oceans around Australia and have the same time span from October 2016 to May 2017. To conduct the cross-calibration, both datasets are referred to the same reference ellipsoid. SLA differences, their mean and standard deviation (STD) are calculated at crossovers formed by single mission of Jason-2 or Sentinel-3A. In order to reduce the impact of ocean variability, we only consider the crossovers whose time lag are shorter than 10 days.

The STD of mono-mission SLA differences at crossovers is used to assess sea level consistency. The results from Sentinel-3A show that the STD of SLA differences at each crossover is dependent on the distance from the coastline, with the averaged value being 9.5cm within 50km off the coast and 6.8cm beyond 50km from the coast. The mean value of SLA differences at each crossover, however, is not affected by the offshore distance with value near zero. The BP retracked Jason-2 SLAs agree with in Sentinel-3A for distance beyond 50km off the coast. Within 50km to the coast, the BP retracked SLA dataset shows a slightly larger STDs, indicating a general performance of the conventional Jason-2 altimeter near shore. The results show that the BP retracked dataset can be confidently used for coastal dynamic research. Although the data quality for both conventional and SAR altimeters are degraded over the coastal area, the better performance revealed by Sentinel-3A demonstrates the SAR waveforms are successfully less contaminated by the coastal morphology.

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Developments in SAR Altimetry over Coastal and Open Ocean: A Retrospective of Developments in SAR Altimetry Processing and the Improvements Achieved through the SAMOSA, CP4O and SCOOP Projects

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The European CryoSat-2 and Sentinel-3A satellites, soon to be followed by Sentinel-3B, were the first to operate SAR mode altimeters. These missions initiated a new era in satellite altimetry over the oceans, in which a step change in improvement in measurements over the open ocean and coastal zone has been achieved, in terms of accuracy of measurement, the capability to map features that could not previously be resolved, and to provide measurements closer to the coast than ever before.

This presentation looks back at a series of three projects initiated by ESA: SAMOSA, CP4O and SCOOP, reviews the development and assessment of new processing schemes for SAR mode altimeter measurements, plots the performance improvements achieved and then looks ahead to further developments.

SAMOSA (SAR Altimetry Mode Studies and Applications) was an ESA-funded project initiated in 2007 to investigate the improvements offered by SAR mode altimetry over ocean, coastal and inland water surfaces, developing practical implementation of new theoretical models for the SAR echo waveform as part of this process.

SAMOSA developed physical based models for SAR altimeter ocean waveforms, and applied them to develop re-trackers for SAR mode products, which were further developed and tested on simulated data, airborne data, and then on real satellite data from CryoSat-2. Approaches to reduce SAR mode data to "RDSAR" data were also investigated, to infer the statistical equivalence between SAR mode and the traditional low-resolution altimetry. Subsequent work further developed the "SAMOSA" model, balancing the aim to improve the modelling of the waveform against efficiency of processing to achieve a practical scheme that could be implemented in the Sentinel-3 Ground Segment.

CP4O (CryoSat Plus for Oceans) was a project supported under the ESA Programme Element coined "Support to Science Element" (STSE) with the objectives to build a sound scientific basis for new scientific and operational applications of CryoSat-2 data, generate and evaluate new methods and products to enable the full exploitation of the CryoSat-2 SIRAL altimeter, extending their application beyond the initial mission objectives, and to ensure that the scientific return of the CryoSat-2 mission is maximised.

Within CP4O, processing schemes for CryoSat-2 data were developed and evaluated for SAR and RDSAR products over the open ocean, and SAR and SARin modes data over the coastal ocean. New geophysical correction products and models (Wet Troposphere, Ionosphere, and Regional Tide Models) were developed and assessed, as was specialized processing of SAR mode data to improve Polar Ocean bathymetry and tidal modelling.

SCOOP (SAR Altimetry Coastal & Open Ocean Performance) is a project funded under the ESA SEOM (Scientific Exploitation of Operational Missions) Programme Element, to characterise the expected performance of Sentinel-3 SRAL SAR mode altimeter products, in the coastal zone and open ocean, and then to develop and evaluate enhancements to the baseline processing scheme in terms of improvements to ocean measurements. Another objective is to develop and evaluate an improved Wet Troposphere correction for Sentinel-3, and 1provide recommendations for use. Recommendations for further developments and implementations are provided through a scientific roadmap.

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Estimated of Background Concentration of Dissolved Oil-Hydrocarbons in the Baltic Sea from Illegal Discharges of Oil-Containing Waste from Ships

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The results of model calculations of the spatial distribution of background concentrations of dissolved oil-hydrocarbons (OH) entering the Baltic Sea from illegal discharges of oily waste from vessels of different types (including tankers) are presented, taking into account advection, destruction, evaporation and deposition of OH. Remote sensing data (satellite altimetry and radiometry) were used as initial information on sea surface current velocities and surface temperature . The value of the OH was calculated on the basis of expert assessments and the spatial distribution of oil spills recorded in the Baltic Sea as a result of aeronautical and satellite monitoring.

The results of the calculations show that the background concentration of OH does not exceed the maximum allowable concentration of 0.05 mg / l. Its average value under the condition of evaporation, destruction and sedimentation was 0.008 ± 0.0004 mg / l, and without taking into account the precipitation, 0.04 ± 0.0017 mg / l. The spatial distribution of the background concentration of OH for the first version of the calculation shows that the maximum values (more observed in the area between Eland and Gotland Island

and the coast of Poland, east of Gotland Island, in Bothnia Bay, north of latitude 64 ° and in the Gulf of Finland between the ports of Helsinki and Tallinn.In the calculations taking into account evaporation and destruction, the areas of these areas are expanding, capturing the exclusive economic zones not only of Sweden, Finland, Poland, Estonia and Latvia, but also Lithuania and Russia (Kaliningrad Oblast).

The proposed approach allows not only to model the spatial distribution of background concentrations of OU, but also to assess the impact of this type of anthropogenic pollution of the Baltic Sea on the ecological situation of the sea as a whole and its coastal waters.

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Interannual Variability of the Black Sea level and Surface Temperature along the Coast of the Krasnodar Krai and the Republic of Abkhazia Based on Satellite Altimetry and Radiometry

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Climate changes in the Black Sea basin and its water area are reflected in changes in the main parameters of the sea state: sea level and sea surface temperature (SST). To study these changes, satellite altimetry and radiometry data were used that allow analyzing the spatial-temporal variability of the interannual rate of change of these parameters over a long time interval. To study the spatial-temporal variability of the rate of SST climatic variability used remote sensing data for two intervals in 1982–2015 and 1993–2015. The results of the study showed that over the time interval 1982–2015 that the SST near the coast of the Krasnodar Krai increase at an average rate of 0.079±0.005°C/yr, and the coast of the Republic of Abkhazia at a rate of 0.072±0.002°C/yr. At the same time, the growth rate of SST decreased from the Kerch Strait (0.082° C/yr) to Adler(0.076 °C/yr), and along the coast of the Republic of Abkhazia decreased from Adler (0.076°C/yr) to Ochamchire (0.071°C/yr). In the shorter time interval of 1993-2015, which coincided with the time interval for the study of the rate of measurement of the Black Sea level, the rate of change in SST also decreased in the direction from the Kerch Strait to the border with Georgia. The results showed that for the time interval of 1993–2015. Sea level off the coast of the Krasnodar Krai increase at an average rate of 0.29±0.03 cm/yr, and the coast of the Republic of Abkhazia – at a rate of 0.27±0.02 cm/yr. The rate of increase in the level of the Black Sea increased from the Kerch Strait (0.28 cm/yr) to Adler (0.31 cm/yr), and along the coast of the Republic of Abkhazia, on the contrary – decreased from Adler (0.31 cm/yr) Up to Ochamchira (0.24 cm/yr).

The reported study was funded by RFBR according to the research project № 17-55-40015_Abh_a «Climate changes of intensity and frequency of extreme hydrological and meteorological events in the coastal zone of the Krasnodar Territory and Abkhazia».

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Processing Method of Satellite Altimetry Data for White, Barents and Kara Seas

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The report focuses on the development of satellite altimetry data processing techniques for the level regime study of the White, Barents and Kara Seas of the Arctic shelf of the Russian Federation. For the study of the Russian Federation the Arctic shelf the best is the choice of satellite altimetry data of ERS-1, ERS-2, ENVISAT and SARAL/Altika, and the White Sea – TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3. It is shown that the systematic error altimetry for the waters of the White, Barents and Kara Seas measurements between satellites ERS-2 c and ERS-1, the average was 1,37±0,94 cm and for EnviSat and ERS-2 satellites − 1.78±0.65 cm. To the White Sea bias between altimetry satellites TOPEX/Poseidon and Jason-1 was 2,61±0,27 cm and for satellites Jason-1 and Jason-2 was -1,83 ± 0,34 cm, and Jason-2 and Jason-3 was +1,52 ± 0,12 cm. Comparison of different tidal patterns showed that the most optimal for the processing of satellite altimetry data are regional tidal model with the maximum spatial resolution.

The reported study was funded by RFBR according to the research project № 18-05-01053_a «Investigation of the hydrometeorological and hydrodynamic regimes of the White Sea based on satellite altimetry».

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Validation of Coastal Sea Level Rates from Dedicated Coastal Altimetry Products

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Validation of coastal altimetry sea level products against in-situ tide gauge measurements is an essential part of verifying the altimetric sea level observations. The introduction of specialised retrackers, such as Adaptive Leading-Edge Sub-waveform (ALES) has improved the estimates of the altimetric sea level rates close to the coast. One way to assess this improvement is via altimetry-tide gauge comparisons, but this is complicated by the fact that the dominant sea level signals at different tide gauges may have very different length scales. Tide gauges located in regions where signals have relatively long cross-shelf length scales generally have a better agreement with altimetry observations and provide a more accurate assessment of the altimeter's performance. Here, as part of a study conducted within the framework of the ESA Sea Level Climate Change Initiative (SL_cci) Project, we identify regions of long length scales based on the high-resolution NEMO (1/12 degree) global ocean model in order to improve the validation technique for assessing the performance of coastal altimetry products from the Jason-1, Jason-2, Envisat and SARAL/Altika missions. The tide gauges are sorted into groups according to their cross-shelf decorrelation values. The performance of the coastal altimetry observations reprocessed with specialised retrackers not yet available in missions' ground segment processors is then assessed for each group of tide gauges separately. An initial assessment by grouping tide gauges in macro-regions shows that there is a very good agreement between along-track altimetry and tide gauges where the sea level variations are correlated over relative large spatial scales such as in south eastern Australia and this is maintained up to approximately 3 km from the coast.

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High Resolution Coastal Wave Model for the West-Indies under Major Hurricanes of 2017

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The West Indies are highly concerned by high sea state with wind sea and swell generated by tropical cyclones and also extra-tropical storms. In the framework of the project HOMONIM the wave model Wavewatch III (WW3) with high resolution up to 200 m has been implemented in 2016 at Météo-France for sea state forecasting in the french islands. A new configuration has been developed in 2018 to extend the domain westerly up to Haïti. The model has the advantage of using an unstructured grid which is very well dedicated to down-scaling and complicated coastline such as the caribbean islands. The high resolution coastal model is nested to the regional west indies wave model MFWAM and is forced by the wind of the mesoscale atmospheric model, Arome, at 2,5 km. The new configuration has been tested during the major cyclones of 2017 : Irma, Maria and Jose. The model has been validated thanks to altimetry wave data on the extended domain. Comparison with altimeters wave heights from Jason-2, Jason-3, Saral and Sentinel 3 showed a good performance of the coastal model. Moreover the use of two wind forcing with different sea surface temperature in Arome is also examined. Waves/currents interaction have been also investigated in particular for the French Guyana which is significantly affected by the ascending brazilian ocean current. Further discussions and conclusions will be commented in the final paper.

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Evaluation of the Impact of High Frequency Radar Data Assimialtion on SSH Forecast

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High frequency radars (HFR) are key observing platforms of coastal Research Infrastructures. They provide high temporal and spatial resolution surface current measurements over wide coastal areas, bringing new insights into coastal processes and helping to assess and improve the performance of ocean models. In particular, the regular and high resolution sampling of HFR measurements make them potentially very valuable inputs for data assimilation in operational systems.

Two coastal HFR sites have been operated by SOCIB (the Balearic Islands Coastal Observing and Forecasting System) since 2012 to monitor the surface currents in the Ibiza Channel (Western Mediterranean Sea). This channel area is a well-established biodiversity hotspot characterized by important meridional flow exchanges with significant impacts on ecosystems. These exchanges result from the complex interaction of different water masses from the surface to deep layers under strong topographic constraints, including mesoscale activity. This makes the Ibiza channel a challenging area from the point of view of numerical modeling.

Several experiments have been carried out to evaluate the improvement in model forecasts when assimilating HFR measurements in addition to multiplatform observations from satellite and ARGO floats, with the objective of being able to be implemented in the operational system. A multimodel Ensemble Optimal Interpolation scheme has been coupled to the SOCIB Western Mediterranean Operational Model (WMOP) to assimilate observations recursively, including HFR surface velocities and along-track SLA data from CMEMS. WMOP is a 2-km resolution configuration of the ROMS model using CMEMS numerical products as initial and boundary conditions and high-resolution surface forcing from AEMET.

The sensitivity to different configurations and initialization methods has been evaluated. A control simulation assimilating multiplatform observations without including HFR velocities allow to characterize the influence of HFR measurements on the forecast performance. Results show the capability of the system to improve SSH forecast when including HFR observations in the assimilation while using a nudging strategy for initialization.

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S3 SAR Mode for Coastal Altimetry. Dedicated Algorithms for Improving Sea Surface Height Series.

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The Coastal Ocean environment is becoming more and more a possible area of study from the geophysical retrievals of altimetry missions. Several initiatives are encouraging a deeper investigation in the coastal altimetry field.

This presentation shows a solution for improving the Coastal Ocean Sea Surface Height (SSH) retrievals using Sentinel 3 SRAL altimeter data.

In the CP4O project (ESA funded) a solution was designed, implemented and tested (http://www.satoc.eu/projects/CP4O/docs/WP1000_SARin&beyond_Coastal_TN_revised.pdf) for improving the CryoSat-2 ESA products SSH data dispersion in coastal areas around the Cuba archipelago.

One of the solutions proposed in the study is here developed further to be used in the S3 altimeter mission.

The preliminary SSH results are analysed and compared to the ESA products outputs.

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GNSS-R Altimetry for Support of Coastal Altimetry

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Since the performance of satellite altimetry is limited in coastal areas, alternative sea height observation methods are required, which are also useful for higher spatial and temporal resolutions necessary for coastal researches. Differential or Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS), which can be used in most coastal areas, is one of the most plausible candidates, but the receiver antennas are necessary to be deployed on the sea. In GNSS reflectometry (GNSS-R), we measure the delay of the GNSS signals reflected at the sea surface with respect to the directly-received one, which is converted to the vertical distance (D_r) between the receiver and the sea surface by assuming a simple geometry, and can be further transformed to the height of the reflection point on the sea away from the receiver if the geo-position of the receiver is known. Experimental GNSS-R flights have been conducted at Lake Biwa, in which the multicopter was hovering about 130 m above the water surface for more than three minutes. In general, the estimated D_r changes in good accordance with the altitude of the multicopter, but it includes significant high-frequency variations of the order of several meters whose periods are several seconds. These periods are similar to those of wind waves, suggesting that the reflection point was displaced due to the slope of the water surface caused by wind waves, which deviates from the assumed simple geometry. After removing these high-frequency variations by temporal averaging, the estimated height of the water surface agrees well with the reference height independently observed by a gauge with 0.07-m difference.

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Assimilation of Altimeter Observations into the Navy Coastal Ocean Model

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The representer method is adopted for solving a weak constraints 4dvar problem for the assimilation of along-track SSH observations, using a the Navy Coastal Ocean Model (NCOM), a free surface ocean model. Direct 4dvar assimilation of SSH observations along the satellite tracks requires that the adjoint model be integrated with Dirac impulses on the right hand side (rhs) of the adjoint equations for the surface elevation equation. The solution of this adjoint model will inevitably include surface gravity waves, and it constitutes the forcing for the tangent linear model (TLM) according to the representer method. This yields an analysis that is contaminated by gravity waves. A method for avoiding the generation of the surface gravity waves in the analysis is proposed in this study; it consists of removing the adjoint of the free surface from the rhs of the free surface mode in the TLM. The information from the SSH observations will still propagate to all other variables via the adjoint of the balance relationship between the barotropic and baroclinic modes, resulting in the correction to the surface elevation. Two assimilation experiments are carried out in the Gulf of Mexico: one with adjoint forcing included on the rhs of the TLM free surface equation, and the other without. Both analyses are evaluated against the assimilated SSH observations, SSH maps from Aviso and independent surface drifters, showing that the analysis that did not include adjoint forcing in the free surface is more accurate. Other assimilation results will be presented for western boundary currents domains (the Gulf Stream, the Kuroshio extension and the Agulhas), and some preliminary work with simulated SWOT observations. This study shows that when a weak constraint 4dvar approach is considered for the assimilation of along-track SSH observations using a free surface model, with the aim of correcting the mesoscale circulation, an independent model error should not be assigned to the free surface.

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Contribution of Satellite Radar Altimetry for Land Deformation Studies

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Satellite radar altimetry, originally designed for deep ocean circulation studies, has been innovatively used to study coastal circulation, tide, ice sheet mass balance, and terrestrial hydrology. Almost a decade ago, TOPEX/POSEIDON radar altimeter was used for the first time, to successfully measure solid Earth deformation undergoing glacial isostatic adjustment (GIA) over the former Laurentide ice-sheet covering Hudson Bay, Canada [Lee et al., 2008]. Since then, decadal or longer satellite radar altimetry has been used to measure land subsidence resulting from anthropogenic groundwater extraction, in Taiwan, Central Valley, California, and North China Plain [Hwang et al., 2016]. The accuracy of deformation measurements, highly depends on terrain gradients, and approaches <1 mm/yr over flat terrain with/without vegetation. Here we extend radar altimeter data span and expand study regions, including the Shangdong coastal transition zone in China, and other coastal regions exhibiting land subsidence caused by sediment compaction/loading. Various waveform retracking and gradient correction techniques as well as the use of SAR and SARIn altimeter data have been used to quantify land subsidence in the regions of interest.

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Last Developments and Perspectives of the X-TRACK Regional Altimeter Products

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Climate change is likely to worsen many problems that coastal environments already face: shoreline erosion, coastal flooding, stress and damage of the coastal biodiversity. Sea level variation is one of the major threat for coastal zones. Improving its observation is essential to better understand and predict the behavior of the coastal ocean. Altimetry provides unique long term observational dataset to characterize how sea level variability evolves from the open ocean to the coastal ocean.

More than 10 years ago, the CTOH (Center of Topography of the Ocean and Hydrosphere) and LEGOS (Laboratoire d'Etudes en Géophysique et Hydrologie Spatiale) started to develop the X-TRACK processing chain in order to recover as more as possible altimetry data in the coastal zones. Now, X-TRACK is a multi-mission product covering all the coastal ocean, freely distributed by the CTOH/LEGOS and by the operational AVISO+ service. Both along-track Sea Level Anomaly time series and along-track empirical tidal constants are available. We present here the latest developments of the product. In particular, it has been decided to inject the L2 ALES (Adaptive Leading Edge Subwaveform Retracker) product in the X-TRACK post-processing algorithm, using the best possible set of altimetry corrections, in order to combine the different efforts that have been done to advance the capabilities of satellite altimetry near coastlines, in a product which will be available for the research community. Here, we will show a first version of this new product as well as its potential for coastal applications.

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Absolute Water Levels at the Estuary of the Karnaphuli River (Bay of Bengal, Bangladesh): Comparison Between Sea / River Surface Heights Gained by GNSS Survey and Satellite Altimetry in Coastal Environment

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The shoreline of the Bengal delta (Bangladesh and India) is a macrotidal area (over 4 m), with a broad (200 km) and shallow shelf. It is also home to marked variability of the water cycle, over a broad range of timescales, from a few hours (cyclonic surges, flash floods) to a few weeks or months (monsoonal floods in the rivers, mesoscale turbulence in the near-shore ocean). Despite profound implications of the water level variability on the society and economy of the 150 M people populating the near-shore region, the characteristics of the ocean tide is poorly observed and understood in this region. Numerical tidal models also do not perform well in this region, compared to the rest of the tropical oceans. This stems, among others, from the lack of knowledge of the bathymetry of the shelf region.

In order to curb this lack of knowledge in the area of the Bay of Bengal along Chittagong, (Karnaphuli River), we performed a survey associating GNSS measurements of the water surface (either it is river water line or sea surface) and leveled bathymetry (by associating the soundings with the GNSS station). In this poster, we present the comparison of the GNSS heights of the water surface with various tidal solutions, including a harmonic analysis of a T/P (CASH reprocessing), Jason1-2-3 (GDRs) series gained close to the shore. In the river mouth, we compare our water levels with measurements collected by SENTINEL-3A (corrected for tides to account for the difference in time between our survey and the overpasses) which track # 193 crosscuts the river in three places of our survey. We also present the cross checking analysis that we performed between the GLOSS tide gauge series in Chittagong and our GNSS profiles.

Wind and Wave Climate from 32-Years of Satellite Altimetry

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Ocean waves are an integral component of air-sea global climate. In addition, waves play an important roles in the nearshore dynamics by driving inundation. Understanding the wave climate and the associated large-scale patterns is of key importance. While the use of altimeter data has typically been driven by the sea level community, these data are of high value to the scientific wave community. For example the significant wave height and means squared slopes have been instrumental in the development of spectral wave models. In this study we focus on describing the wind and wave climate over the past several decades from satellite altimetry.

The 32-years of wind speeds and wave heights (1985-2016) from altimeters is an attractive source of data for wave climate studies. We focus on two aspects of the wave climate: 1) seasonality and 2) inter-annual variability. The seasonal cycle is of course linked to the distribution sun's energy throughout the year. We observe intricate regional patterns of the seasonal cycle where higher order harmonics play an important role. For example, in the Northern Hemisphere the wave seasonal cycle follows a simple sinusoid while in the Southern Ocean a long flat winter with only a short summer is observed. Now with a more precise removal of the seasonal cycle we can better isolate inter-annual variability. We find regional patterns of inter-annual variability across the ocean basins related to the North Atlantic Oscillation, El Nino Southern Oscillation, and Southern Annular Mode confirming previous studies which were based on wave hindcasts. The Southern Ocean has the largest inter-annual variability.

A key concern in use of satellite altimetry is the time-space sampling and the consistency of the multi-mission dataset. These points are discussed within the context of the ESA Sea State CCI+.

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Wave Steepness from Satellite Altimetry for Wave Dynamics and Climate Studies

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Wave steepness is presented as an extension and a valuable add-on to the conventional set of sea state parameters retrieved from satellite altimetry data. Following physical model based on recent advances of weak turbulence theory wave steepness is estimated from directly measured spatial gradient of wave height. In this way the method works with altimetry trajectories rather than with point-wise data. Moreover, in contrast to widely used parametric models this approach provides us with instantaneous values of wave steepness and period. Relevance of single-track estimates of wave steepness (period) is shown for wave climate studies and confirmed by a simple probabilistic model. The approach is verified via comparison against buoy and satellite data including crossover points for standard 1 second data of Ku-band altimeters. High quality of the physical model and robustness of the parametric ones are examined in terms of global wave statistics. Prospects and relevance of both approaches in the ocean wave climate studies are discussed.

Global spatial distributions of wave steepness within the parametric and physical approaches are presented for the first time. These distributions discover an intriguing feature of wave steepness: its geographical climatic variability is remarkably low in contrast to conventional wave parameters (wave height and period) that show pronounced regional (first of all, latitudinal) dependence. This universality looks promising though it requires further thorough analysis.

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CFOSAT : A New Satellite for Ocean/Atmosphere Interaction Research and Operational Oceanography

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The Chinese and French Space Agencies are jointly preparing an innovative satellite mission, CFOSAT (China France Oceanography Satellite) devoted to the monitoring of the ocean surface and its related science and operational applications. CFOSAT will provide global observations of surface wind and spectral characteristics of the surface ocean waves (energy as a function of direction and wavelength) by using a combination of nadir, near-nadir (2°-10°) and off-nadir (20-50°) Ku-Band measurements in a azimuthally rotating geometry.

The objective is multifold. It will serve both operational needs for the meteorological (NWP) and wave forecast, and research needs to improve our knowledge on the hydrodynamics of the waves, on the interactions between waves and the atmospheric or oceanic layers close to the surface.

WIth CFOSAT, for the very first time, both wind and wave vectors will be measured at the global ocean surface. This will be achieved thanks to the two-instruments, both of them being innovative instruments in terms of geometry and design:

- SWIM (Surface Wave Investigation and Monitoring) a near-nadir (nadir beam and 2 to 10° incidence beams) real-aperture Ku-Band azimuthally scanning radar designed for measuring the directional spectra of ocean waves,-SCAT a wind scatterometer SCAT to measure the wind vector, radar in Ku-Band aiming at moderate incidence angles (26° to 46°) with a rotating fan-beam antenna.

Both payloads are presently under assembly and test. The satellite will be launched in September 2018.

During the conference we will point out the originality of these measurements, their complementarity with other existing satellite observations, (in particular altimeter measurements) and their interest for research on the wave modulated air/sea exchanges. Expected improvements on operational wave forecasting will be also addressed. We will also show results based on simulated products.

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Radar Altimeter Signatures of Internal Solitary Waves in the Ocean

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Short period nonlinear internal waves or Internal Solitary Waves (ISWs), whose periods are an order of magnitude smaller than tidal internal waves, are generally assumed too small to be detected with standard altimeters (at low sampling rates, i.e. 1 Hz). This is because pulse limited Radar Altimeter (RA) footprints are somewhat larger, or of similar size at best, than the ISWs typical wavelengths. However, it has been recently demonstrated that new generation high sampling rate satellite altimetry data (i.e. ~20 Hz) hold a variety of short-period signatures that are consistent with surface manifestations of ISWs in the ocean (Magalhaes and da Silva, 2017). The observational method was based on satellite synergy with imaging sensors such as Synthetic Aperture Radar (SAR) and other high-resolution optical sensors (e.g. 250m resolution MODIS images) with which ISWs are unambiguously recognized. Straining of decimeter to centimeter-scale surface waves due to ISW orbital currents is known to cause roughness variations along internal wave propagation fields. This effect was demonstrated by measurements of wind wave slope variances associated with short-period ISWs in the pioneer work of Hughes and Grant (1978). Mean square slopes can be estimated from nadir looking RAs using a geometric optics (specular) scattering model (Brown, 1990; Jackson et al., 1992; Frew et al., 2007), and directly obtained from backscatter (sigma0) along-track records. Furthermore, high resolution along-track SAR (Synthetic Aperture Radar) mode altimetry and simultaneous OLCI (Ocean Land Colour Imager) data from Sentinel-3A reveal short-period oscillations, which are identified as oceanic ISWs. Their rough and slick patterns arrayed in parallel bands over successive crests and troughs underneath, introduce measurable perturbations in the along-track sharpened SAR altimeter's footprint. The resulting (Level-2 SAR mode) geophysical parameters are significantly altered in the ISWs' vicinity, but yet yielding realistic estimates when compared with previous observations reported for conventional pulse-limited altimeters (Jason-2). We use differential scattering from the dual-band (Ku- and C-bands) microwave pulses of the SRAL to isolate the contribution of small-scale surface waves to mean square slopes. The differenced altimeter mean square slopes estimate, derived for the nominal wave number range 40–100 rad/m, is then used to detect roughness variations in records of the SAR mode along-track Sentinel-3 altimeter. Subsequently these high-frequency signatures are compared with simultaneous OLCI imagery with imprints of ISWs. The validation of those RA signatures as ISWs lead us to develop an automatic detection algorithm based on wavelet transforms that is capable to detect ISWs. In addition, since pulse limited radar altimeters can be viewed as high resolution imaging instruments whose geometry is annular and not rectangular, a method based on the computation of the imaging matrix and its pseudoinverse to infer the surface backscatter at high resolution (300 m) from the measured waveforms (Tournadre et al., 2011) has been applied to the case of ISW observations in Jason-2 data. The method confirms the existence of radar backscatter variations consistent with ISW patterns on the ocean surface.

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Advances in Using Satellite Altimetry to Enhance Monitoring and Prediction of Storm Surges

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Storm surges are the major cause for coastal flooding, resulting in catastrophic damage to properties and loss of life in coastal communities. Thus it is important to utilize new technology to enhance our capabilities of observing storm surges and ultimately to improve our capacity for forecasting storm surges and mitigating damage and loss. Storm surge has long been observed by coastal tide gauges, high-water marks and pressure gauges. Numerical models have been used to provide operational real-time forecasts of the timing and magnitude of storm surge, providing the scientific basis for issuing flood warnings. Tide gauge data are most reliable and have been used to understand storm surge features. However, tide gauges are quite sparse and not installed in some coastal communities. During extreme storm surges, typically reliable tide gauges may not work properly or fail completely. For example, during Hurricane Katrina, many tide gauges failed along the New Orleans and Mississippi coasts. Therefore, timely and accurate observations from other sources would be useful to complement tide-gauge data for monitoring storm surges and for improving model prediction. Satellite altimetry provides all-weather sea level measurements globally. While its data quality deteriorates few tens of kilometers from coast, it provides useful information over the continental shelf and in the deep ocean where tide gauge data are not typically available. In recent years, a variety of experimental coastal altimetry products have been developed, which may reach a few km from shore. We present examples of storm surges observed by nadir satellite altimetry, during Hurricane Sandy off New York, Hurricane Isaac in the Gulf of Mexico, as well as typhoon and cyclone events elsewhere. We show how and how well satellite altimeter data can be used to derive coastal storm surge features. We further present examples on how the altimeter observations can be used to improve storm surge modelling. Finally, we discuss the potential of a wide-swath altimetry mission, the Surface Water and Ocean Topography (SWOT), for observing storm surges.

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The Sea State Climate Change Initiative project

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Sea state, i.e. the description of waves and swell in terms of height, wavelength, period and direction, is one of the Essential Climate Variables (ECVs) for which GCOS has laid out stringent observation requirements. Monitoring of this ECV is needed for climate research both because of its role in modulating ocean/atmosphere exchanges and in the global cycles of energy, water and carbon, and because of the impacts of sea state on society (coastal flooding, marine safety, marine transport, erosion, effects on ecosystems). Satellite remote sensing is the primary source of sea state observations over the oceans. These observations must be complemented and validated by in situ measurements, and for some regions and periods they can also be combined with seismic records. Today the 25-years long record of satellite altimetry makes it possible to analyze the wave climate at global to regional scales. The record is also critical for validating models used for finer scale wave analyses and forecasts of relevance, for instance, applications by coastal management and shipping. To respond to the GCOS requirements for this important quantity ESA has just launched a new project on the "Sea State" ECV as part of the CCI+ program. A primary concern of the project will be the accuracy and stability of the multi-mission data sets. These include significant wave height from satellite altimeters that comprise-in the initial 3-year phase of the project-all the ESA missions and the Jason series since 2002, and wave spectra from radar imagery: all wave mode from ERS to Sentinel 1. The study has the potential to provide the definitive Climate Data Record for Sea State but it is also very challenging as until now sea state has never been the main focus of satellite altimetry. Except for the results of the Globwave project and new CMEMS activities, wind and wave parameters from altimeters were a by-product of sea level estimates, leading to inconsistencies between sensors and satellite missions. The Sea State CCI Project will thus carry out algorithm development to ensure the best possible quality of wave and wind products with a particular focus on consistency.

The rapid evolution of measurement techniques, in particular going from conventional pulse-limited to Delay-Doppler (SAR-mode) altimetry, is a great opportunity to define the standards for future climate records. We will work towards harmonizing the processing to arrive at seamless products than span the years 2003 to 2020 in phase 1, making possible longer time series that go further back in time in a future phase 2.

This project is one piece of the witer CCI+ program, and we will work with the Earth observation and climate science community to identify and better analyse key processes that contribute to uncertainties in other ECVs (primarily sea level and sea ice).

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Status of the Surface Wave Investigation and Monitoring (SWIM) Instrument

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The Surface Wave Investigation and Monitoring (SWIM) instrument developed by Thales Alenia Space was delivered to CNES in September 2017 in the frame of the CFOSAT (China France Oceanography Satellite) mission. The goal of the CFOSAT mission is to monitor the ocean surface winds and waves in order to improve the forecast for marine meteorology (including severe events), the ocean dynamics modeling and prediction, the knowledge of climate variability, and the knowledge of ocean surface processes linked to wind and waves.

SWIM is a real aperture Ku-band radar dedicated to the study of the waves. The instrument presents a rotating antenna intended to transmit signal towards the nadir direction of the satellite and towards five distinct directions with the following incidence angles: 2°, 4°, 6°, 8° and 10°. Such a configuration allows to scan the whole azimuth angles (0° to 360°) and provides with a filled 180 km wide swath. SWIM is going to provide 1D range sampled echoes, from which an adequate ground processing leads to the retrieval of wave spectrum characteristics and of radar cross-section profiles with respect to the incidence.

SWIM presents several technological innovations. A specific echo tracking processing is implemented in order to track 6 echoes from 6 different incidences. In order to ensure wave spectrum retrieval and to reach the specified radiometric performances, several new features have been implemented. First, a rotating antenna with a very stable rotation speed of 5,6 round/min has been specifically developed. This antenna can be commanded in rotation or can be stopped at a fixed azimuthal position. Then, on-board migration correction for echoes of high incidences from 6° to 10° has been implemented. Finally a specific calibration strategy using 3 calibration paths has been implemented to retrieve the backscatter coefficients with an absolute accuracy better than ±1dB, and with a relative accuracy between different beams better than ±0.2dB. Functional and performances validation of the SWIM instrument have been successfully carried out during the test campaign of the stand-alone SWIM instrument that took place from December 2016 to September 2017. The paper will present the overall architecture and some key results of the testing prior to the delivery of the instrument.

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Ocean Wave Data Assimilation at ECMWF: A Review

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Operational ocean wave data assimilation at the European Centre for Medium-Range Weather Forecasts (ECMWF) started on 15 August 1993 (Janssen et al., 1997) with the assimilation of the radar altimeter significant wave height (SWH) obtained from ERS-1 of the European Space Agency (ESA). The assimilation scheme is based on the sequential optimum interpolation (OI) procedure (Janssen et al., 1989, 1997 and Lionello et al., 1992). Later on, altimeter SWH from ERS-2, ENVISAT, Jason-1, Jason-2, CryoSat-2, SARAL/AltiKa were added to the system after they became available. Furthermore, wave spectra from the Synthetic Aperture radar instruments on-board ERS-2 and ENVISAT were also assimilated. Bias correction is very crucial for the success of data assimilation for SWH data of altimeters. This was clear from the forecast degradation when biased altimeter data were assimilated (especially from Jason-1 and CryoSat-2). A recent development in data assimilation at ECMWF is the inclusion of altimeter SWH data from the recently launched Jason-3 and Sentinel-3A.

The Copernicus Evolution and Applications with Sentinel Enhancements and Land Effluents for Shores and Seas (CEASELESS) project, which is part of the Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020), has just started. Within the framework of this project, work will be carried out to improve wave data assimilation. Other data assimilation approaches, e.g. variational methods, and adaptation of data assimilation with wave models that implementing unstructured grids. The currently used definitions for the error covariance matrices and decorrelation lengths needed for data assimilation will be reviewed and improved alternatives will be tested.

The status of ocean wave data assimilation and the impact of altimeter wave height data assimilation will be reviewed. The future plans (with results if available in time) supported by the CEASELESS project will be summarized.

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Impact of vertical sea wave orbital velocities on SAR Altimetry

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Since the start of the CryoSat-2 mission, systematically processed with the unfocused SAR technique, the precision of retrieved geophysical parameters has increased. However, comparison with reduced SAR (also known as pseudo low resolution mode) altimetry shows a discrepancy in significant wave height measurements dependent on the sea state.

This study addresses these differences by introducing the vertical wave orbital velocity as a normal distributed random variable. Its standard deviation is going to be considered as a free parameter during the retracking of the unfocused SAR waveforms. Several approaches are tested to find the best possible way of estimating the standard deviation of the vertical wave orbital velocity. We use three different methods: Hamming weighting, introducing the range integrated power into the retracking and introducing the SWH values computed within a reduced SAR data processing.

The test area for this study is the German Bight and the geophysical parameters estimated are sea surface height, significant wave height, standard deviation of the vertical wave orbital velocity and the wind speed. These parameters are validated against tide gauge and buoy data.

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New Wave Near-Real-Time Observational Products Derived From Altimetry and SAR

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A new near-real-time wave service started in July 2017 in the frame of the Copernicus Marine Environment Monitoring Service (CMEMS). It provides Level-3 along-track significant wave heights issued from different altimeters: Jason-3, Sentinel-3A, Saral/AltiKa and soon Cryosat-2.

This service is operated by CLS, relying on a Level-3 altimetry wave chain, adapted from the CMEMS/DUACS chain operated for sea level products. Upstream Level-2 wave data are processed to provide state-of-the-art calibrated wave products. First, only valid data are included, based on a rigorous editing combining quality flags and thresholds. Then, all the missions are homogenized with respect to a reference mission which is currently Jason-3. And finally, all the missions are calibrated on in-situ buoy measurements.

Altimetry wave parameters are available on CMEMS catalog approximately 3 hours after the measurements.

Wave dynamics happen on a short time-scale and this near-real-time constraint is therefore essential to allow an effective data assimilation for wave forecasting services. Besides, this service will soon provide data from four operational altimeters: the increased density of observations will not only improve model forecasts but also add resilience to the altimetry observing system.

This wave service is now expanding its scope to two new types of products: Level-4 gridded significant wave heights derived from altimetry and Level-3 spectral integral parameters derived from Synthetic Aperture Radar (SAR).

Level-4 gridded products will provide daily multi-mission maps of significant wave heights, ready-to-use to explore the short- to long-term variability of wave conditions or to identify interesting structures.

SAR Level-3 products will soon be available for the Sentinel-1A and 1B missions and will provide near-real-time wave height, period and direction at the peak of each identified wave partition. Unlike wave parameters derived from altimetry, SAR allows to work on different parts of the wave spectrum and therefore to distinguish swells generated remotely by different storms from waves generated by local wind. This new product will allow to investigate further wave dynamics, specific storm events and will provide more precise wave parameters to wave modelers, both for data assimilation and model validation purposes.

Besides feeding operational forecasting systems, this near-real-time wave service and its upcoming products can also be used for various applications: analysis of short- to long-term variability of wave conditions, statistics of extreme wave events, design of offshore and coastal structures, study of coastal morpho-dynamics, etc. To support the growing interest in quality observational wave products derived from satellites, this service will evolve with the satellite constellation and with technical developments. For example, the feasibility of a higher spatial resolution or a higher precision nearshore will be explored.

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Synergy between Satellite Observations and Model Simulations during Extreme Events

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In this study the quality of the wind and wave data provided by the new satellite Sentinel-3A is evaluated. The focus is brought to the coastal areas, where altimeter data are of lower quality than in the open ocean. Satellite data of Sentinel-3A, Jason-2 and CryoSat-2 is assessed in a comparison with in-situ measurements and the spectral wave model (WAM) simulations. The sensitivity of the wave model on wind forcing is evaluated, using data with different temporal and spatial resolution, such as ERA-Interim and ERA5 reanalyses, ECMWF operational analysis and German Weather Service (DWD) forecast. Numerical simulations show that the wave model forced with the ERA-5 reanalyses as well as the ECMWF operational analysis demonstrate the best skill over the whole study period, as well as during extreme events. In order to further estimate the variance of the significant wave height of the ensemble members with different wind forcing, especially during extreme events, an Empirical Orthogonal Function (EOF) analysis is performed. Inter-comparisons between remote sensing and in-situ observations demonstrate that the overall quality of former is good over the North Sea and Baltic Sea during the whole study period, although the significant wave height from the satellites tends to overestimate the one of in-situ measurements by 7 cm to 30 cm. The quality of all satellite data near the coastal area decreases, however, within 10 km of the coast, Sentinel-3A performs better than the other two satellites. Analyses have been carried out, in which data from the satellite tracks are separated between onshore and offshore flights. No substantial difference is found when comparing the statistics for the onshore and offshore flights. No substantial differences have been also found between the satellite tracks under varying metocean conditions. It can be concluded that the quality of the data in coastal areas has improved for the new Satellite Sentinel-3A compared to older satellites. Furthermore, the prediction limits and applications for the combination of newly available satellite observations, in-situ data and model simulations is addressed.

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From Gravity Waves to Mesoscales: Broadband Measurements of Ocean Surface Topography Using Airborne Lidar Technology

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With the growing interest in understanding air-sea interaction, upper ocean dynamics and thermodynamics, increasing emphasis has been placed on submesoscale ocean processes. As the remote sensing community moves to higher spatial resolution (e.g. the Surface Water and Ocean Topography, SWOT, mission), the surface wave field will become of more significance both for the dynamics and for the sea-state bias corrections since the wave field correlates with the submesoscale dynamics through wave-current interaction. In this regime of ocean dynamics, some of these needs can be met by the use of airborne lidar for the measurement of ocean topography from mesoscales of O(100) km to gravity waves of wavelengths O(10) cm. Here we present results from a series of experiments conducted over the past 7 years using the Modular Aerial Sensing System (MASS), an airborne instrument package developed at the Scripps Institution of Oceanography. Airborne lidar measurements of sea surface topography ranging from submeter- to meso-scales, synchronized with satellite altimeter overflights off the coast of California and in the Gulf of Mexico are analyzed, along with coincident airborne hyperspectral and infrared imagery to characterize the changes in sea surface topography and surface wave variables. The implications of the results for future high resolution satellite altimeters are discussed.

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Mixing, Restratification and Heat Uptake in Tropical Cyclones Wake: Processes and Contribution of Multiplatform Satellite.

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Tropical cyclones (TCs) moving above a warm ocean represent extreme cases of ocean-atmosphere interactions. TCs are known to generate surface waves higher than 15 m, longer than 300 m, upper-ocean currents of 1 m/s, sea-surface temperature cooling of several degrees, changes in sea surface salinity, but also, and often overlooked, sea-surface height depressions (trenches) as large as 50 cm. Today, these primary features of the ocean response to a moving TC system can be analysed owing to the combined use of satellite observations, including altimeters, medium- to high resolution radars, as well as passive microwave measurements. While both physics of the ocean surface and of the remote sensing measurements under extremes are still imperfectly understood, this ensemble of observations constitutes a virtual constellation to more precisely depict TC forcing conditions and discuss the scales of the resulting TC's induced oceanic variability. First, a new parametric upper ocean-forcing model can be derived using the unique capability of Synthetic Aperture Radar (SAR) imagery, to obtain more reliable high-resolution TC descriptions (i.e. eye-wall, maximum wind radius, ...), further possibly constrained using altimeter sea state estimates and rain-free L-band passive radiometer measurements. After the TC passage, both surface salinity and temperature observations can be used. Moreover, the oceanic response is also analysed in term of sea level anomaly (SLA), using the full potential of the present altimetry fleet. As expected, SLA signals are good markers of the TCs ocean dynamics, containing both flux components (Ekman transport) and steric changes in their signatures. Completing the satellite observations, Argo profiles add valuable information for a better description of the mixed layer dynamics. Complementing analytical model solutions, this enhanced observations-driven framework will be described and shown to have the potential to bring new insights and a renewed climatological point of view on the heat balance and re-stratification mechanisms in TC's wake.

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Characterization of the Wind Drop-Off in Coastal Eastern Boundary Upwelling System Using Surface Winds from Radar Altimetry

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Surface winds intensity is derived from radar altimetry backscattering coefficient as they affect the amplitude of the return pulse echo. As the sea surface becomes rougher, the number of reflecting faces decreases and more energy is scattered back in off-nadir directions with increasing wind speed. This leads to a decrease in the amplitude of the mean backscattered power, which can be related to the surface wind speed. Due to inherent limitations of the altimetry missions (low spatial and temporal resolutions) for addressing synoptic-scale, they are not as commonly used as surface winds from scatterometers. However, the narrower altimeter footprint allows resolving the 25-50-km fringe along the coast, thus improving near-shore wind retrievals with respect to scatterometer capability where along-shore wind is usually observed to decrease on-shoreward (which is referred to as the wind drop-off). Along-track altimetry-derived surface wind speed data from ENVISAT, Jason-1, Jason-2, and SARAL satellites are usedto document the spatial variability of the mean wind drop-off near the coast as estimated from the inversion of the radar backscattering coefficient in the major eastern boundary upwelling systems (Chile-Peru, California, …) where this wind drop-off is influential on the oceanic dynamics. Results of calibration against scatterometer observations of previous and current satellite missions (QuikSCAT, ASCAT) offshore and buoy measurements are presented. Analyzing the results of the calibrated data off, the wind drop-off characteristics were estimated indicating a significant alongshore variability in its magnitude. The relative contribution of Ekman pumping and Ekman transport to the total transport is also estimated showing that in general that the Ekman pumping compensate for the decrease in Ekman transport associated to wind drop-off. We illustrate that this compensation effect may hide significant differences in the circulation based on sensitivity experiment with a regional oceanic model of the central Chile region. Despite the aliasing effect associated with the weak repetitivity of the satellite orbit and the high frequency variability of the winds in this region, the analysis suggests that the seasonal cycle of the surface winds near the coast could be resolved in some regions.

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Assessment of Severe Waves with Satellite Altimetry Data and Doppler Radar Observations in the North Sea.

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Assessment of severe waves with satellite altimetry data and Doppler radar observations in the North Sea.

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Abstract

We revisit a previous study of the North Sea winter storms (Ponce de León et al 2017) in order to compare numerical simulations using a spectral wave model (WaveWatch III, Tolman (2014)) with Doppler radar measurements and satellite altimetry data from different missions (JASON1, JASON2, SARAL, CRYOSAT). Measured and modeled time series of integral wave parameters and directional wave spectra are compared for a 12-day period in the winter of 2013-2014. A good general agreement was obtained for the integrated parameters, but inconsistencies were found to occur in spectral shapes.

Keywords: Wind waves, Doppler wave MIROS radar, WAVEWATCH III, North Sea, JASON1, JASON2

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Mean Dynamic Topography Determination Using Saral/Altika Altimetry Data and GOCE Gravity Model

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Altimeter is an instrument used to accurately measure the sea surface height. The objectives of altimeter mission are to realize precise, repetitive global measurements of sea surface height. Among objectives of Saral/Altika satellite, most specific concerns the survey of the oceans dynamic topography

The Mean Ocean Dynamic Topography, which is the distance between the Geoid and the Mean Sea Surface (MSS) and which reflects the ocean dynamics, is a primary oceanography unknown.

The processing of 3 years altimetry satellite measurements of Saral/Altika satellite, from January 2015 to November 2017, by the correction of the environmental, geophysical and orbital effects, permit us to determinate the Mean Sea Surface, while using a Gravity model based on 03 years of GOCE satellite observations, we can calculate the Mean Dynamic Topography over the Western Mediterranean Sea.

The variation of the obtained surface is between -0.35 and 0.28 m, with an average of 0.08 m and a standard deviation = 0.12 m. The dynamic topography is much important on the Mediterranean coast compared to the wide and it is more important on the south of the western Mediterranean relative to the north. The obtained surface is compared with SMDT-MED-2014, the mean dynamic topography over the Mediterranean sea, produced by CLS Space Oceanography Division and distributed by Aviso Altimetry.

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Mean Sea Surface: A Constant Evolution over the Last 25 Years.

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MSS determination is a multiple challenging. It is by definition the steady state of the ocean which is used as a reference field for oceanographic and geophysical studies. Since 1994, when ERS-1 was placed in a non-repetitive geodetic orbit, the path for mapping the shortest wavelengths of the marine geoid has become publicly available. Nowadays, with data from cryosat-2, Jason-1, and SARAL in the geodetic phase, we have recent observations that allow us to map the finest geophysical structures with significantly improvement of both spatial coverage and accuracy.

However, one of the major challenges remains the removing of the seasonal and interannual ocean variability which is theoretically accessible only from repetitive missions (T/P, ERS-2, Jason-1/2/3, EnviSat, and Sentinel-3A). The difficulty in determining the MSS is therefore to implement methods that provide us with the best compromise between the removal of temporal variability and an accurate mapping of the shortest wavelengths of the topography.

An overview of the evolution of the precision and the spatial resolution of the MSS is proposed, from the late of the 1990s to the present day.

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Mean Sea Level and Mean Dynamic Topography Determination From Cryosat-2 Data Around Australia

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Determination of Mean Sea Surface (MSS) is of a great importance in some geodesy and oceanographic applications and a couple of centimeters would change the calculated parameter significantly. The dense spatial coverage of Cryosat-2 data offers the opportunity of investigating the Sea Level Anomaly (SLA) over ocean in higher resolution from a single mission data. In other words, although multi mission data sets may have a considerable spatial density, the variation in data set qualities from different missions make the processing difficult, particularly in crossovers. Despite the fact that the main aim of Cryosat-2 mission is monitoring the thickness of ice sheets, it is also used over oceans for different purposes.

To study the contribution of the Cryosat-2 data around Australia, 6 years data set of this mission are used. As the SSH values are too large in magnitude and any small variations would not be appeared clearly in the analysis, to investigate the changes, SLA based on DTUMSS13 model is analysed as the main parameter. The strong striping effects, particularly in Gulf Carpentaria and South East, characterizes a substantial part of the map. This, in fact, implies presence of a strong periodic signal in the SLA data. The main reason behind the strong striping in the Gulf Carpentaria is related to presence of annual signal. To solve this issue, the annual signal should be extracted from the SLA data so that all of them refer to the same epoch of the year. The determined annual signal amplitude from Topex/Posseidon and follow-on missions are interpolated into the Cryosat-2 data points. The subtraction of constructed annual signal from the SLA of Cryosat-2 data reduce the striping effect substantially though a slight averaging is required to eliminate it completely. The final product represents a smooth mean SLA. The mean SLA is then added to DTUMSS13 to provide us with the MSS model of Cryosat-2 data. This MSS model is used to calculate the mean dynamic topography around Australia.

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Indirect Mapping of Sub-Water Interfaces Derived from Satellite Altimetry: from Seafloor to River Channels

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Mapping the floor of the oceans has been a spectacular -unexpected- result of satellite altimetry. It was gained indirectly by assimilating sea surface undulations to surface gravity variations due to mass anomalies based on the seafloor; and inversion of Newton's law. Quantities such as the rock densities, the plate stiffness had to be prescribed. Similarly, river bathymetry can be mapped indirectly using satellite altimetry. For rivers, instead of Newton's Law of Gravity used for the oceanic floor, we use the Manning power law that relates the variations in height and slope of the water surface to the flow in the channel in a so-called rating curve. Prescribing a realistic value for the Strikler-Manning roughness cofficient, the parameters of the rating curves best-fitting the altimetry-discharge pairs inform on the mean elevation of the river bed and on the geometry of the cross section. Today, the method is limited to specific points (Virtual Stations) along the river but can be guessed between VSs assuming geomorphological relationships between rating curve parameters, similarly as ocean bathymetry is gained only along satellite tracks and combined with shipborn data elsewhere.

In the present study, we present in-depth the methodology to gain river bathymetry from satellite altimetry that we have developped in order that full mapping of the river beds and seafloor are achieved jointly by SWOT.

This approach based on Manning-Strickler law reveals to be a first highly complementary step with full hydraulic models (Shallow Water) in view to extrapolate information in space-and time in a context of assimilation of the future SWOT data. Building this information thus appears as essential for modeling the river flow as the seafloor bathymetry is for the modelling of the oceanic dynamics.

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A Coastal Mean Sea Surface with Associated Errors along the Norwegian Coast Based on New-Generation Altimetry

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The coastal mean sea surface (MSS) has applications within oceanography as well as geodesy. Together with a geoid model, it forms an important component for geodetic mapping of ocean surface currents that are in geostrophic balance. Furthermore, it forms a bridge between open ocean MSS and in situ measurements of mean sea level at or close to land, it contributes to the mapping of the geoid and the marine gravity field, and it is essential for connecting tidal nautical chart datums to physical height systems or global geodetic reference frames.

In this study, we determine a coastal MSS with an associated error field for Norway. The MSS is solely based on new-generation altimetry data, i.e., SAR(In) data from Sentinel-3A and CryoSat-2, as well as Ka-band data from Saral/AltiKa. The data sets partly overlap in time and cover the time period from 2010 to 2017 inclusive. We have chosen these altimeters because they represent evolutions of conventional altimetry, with reduced footprint diameters as a main benefit. This is especially advantageous in the coastal zone, as a smaller footprint reduces the probability of radar pulses being contaminated by energy backscattered from land areas.

The satellite missions were harmonized by applying inter-mission biases calculated in a regional crossover-analysis. Furthermore, in a zone closer to land than 25 km, we have replaced the global ocean tide model with a regional ocean tide model provided by the Norwegian Mapping Authority. We explore different data editing strategies, compare two methods for optimal interpolation of the along-track data to a regular grid, and discuss these in the context of the estimated error field.

We assess our coastal MSS by comparison to existing state-of-the-art MSS products, as well as ellipsoidal mean sea level as observed by an array of tide gauges within the study area.

The Norwegian coast is characterized by thousands of small islands, narrow fjords, rough topography, and complex tidal patterns, making the altimetric measurement of the sea surface height particularly demanding in this area.

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Improved Arctic Ocean Bathymetry and Regional Tide Atlas – a CP4O Initiative.

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CryoSat Plus for Oceans (CP4O) is a project under the ESA STST program which aims to develop and evaluate new ocean products from CryoSat data and so maximize the scientific return of CryoSat over oceans. The main focus of CP4O has been on the additional measurement capabilities that are offered by the SAR mode of the SIRAL altimeter, with further work in developing improved geophysical corrections.

The Arctic Ocean is a challenging region, because of its complex and not well-documented bathymetry, together combined with the intermittent presence of sea ice and the fact that the in situ tidal observations are scarce at such high latitudes. The current initiative initially addresses the bathymetry in the Arctic in attempting to improve altimetric bathymetry using the near 7 years of Cryosat-2 high quality and high resolution ”geodetic” SAR altimetry all the way up to 88N. Subsequently the project progresses to use Cryosat-2 in TWO ways for improved ocean tide modelling in the Arctic Ocean. One is to use Cryosat-2 improved bathymetry the second is to use Cryosat-2 derived harmonic tidal constituents for assimilation into a regional tide model.

The first project bathymetry in the Arctic will be presented and evaluated in this presentation. It will also present the methodology to derive bathymetry from the high resolution DTU17 marine gravity field derived from Cryosat-2. Secondly this presentation highlights the methodology followed to develop the model and the performances of this new regional tidal model in the Arctic Ocean.

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A New DTU18 MSS Mean Sea Surface – Improvement from SAR Altimetry

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In this presentation we outline the new DTU18MSS mean sea surface which is the latest release of the global high resolution mean sea surface from DTU Space. The major new advance leading up to the release of this DTU18MSS the use of 3 years of Sentinel-3A and an improved 7 years Cryosat-2 LRM record. A new processing chain with updated editing and data correction (i.e., using FES2014 as Ocean tide model) has been implemented. The use of consistent ocean tide model for the Mean sea surface and the subsequent processing of sun-syncronous satelliites has proven to be important to reduce the error that the MSS contributes to the total error budget.

The presentation will also also focus on the difficult issues as consolidating Cryosat-2 and Sentinel-3 onto a past 20 year mean sea surface derived using multiple LRM satellites as well as the importance of merging Cryosat-2 data from different operating modes like LRM, SAR and SAR-In as these requires different retrackers.

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High resolution Gravity Field Modelling Using SAR Altimetry in the Northeast Atlantic Ocean.

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Over the past year SHOM, DTU Space and Noveltis has corporated on updating altimetric data and on the use of these for gravity field modelling in the Northeast European shelf. The joint investigating har particularly focused on studying the effect on the use of SAR altimetry from the Cryosat-2 mission which is operating in SAR mode in the Northeast part of the Atlantic Ocean. In this presentation we investigate the effect of using SAR altimetry for marine gravity field modelling in comparison with RDSAR altimetry.

We select CryoSat-2 altimetry products over a time interval of 6-years from October 2010 to December 2016 along the Northeastern coasts of the Atlantic

Ocean. The ESA GPOD processors SARVatore was applied to retrack the 20 Hz Cryosat-2 SAR. The SAMOSA-2 (Ray et al., 2014) and SAMOSA+ SAR products have been evaluated in the presentation. They initially differ in the way the SAR waveforms are build (i.e. Hamming weighting window on the burst data prior to the azimuth FFT, zero-padding prior to the range FFT, doubling of the extension for the radar range swath) and in the retracking methodology.

The Cryosat-2 waveforms were turned into conventional LRM like data and the RDSAR waveforms have been retracked by the RADS altimetry system and this dataset were also introduced into the validation in order to investigating the effect of using SAR altimetry using two near-similar datasets.

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Global and Regional Evaluation of the First Two Years of Sentinel-3A and Very First Sentinel-3B and the Impact of Mean Sea Surfaces and Ocean Tide Corrections.

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The use of a mean sea surface is paramount for deriving sea level anomalies from satellite altimetry. Sentinel-3 offers independent SAR altimetry along new ground tracks and can hence provide independent evaluation of existing mean sea surfaces. We perform an evaluation of the recent available mean sea surfaces using one year of 1 Hz Sentinel-3A data taking into account the shift in temporal average and coverage. Sentinel-3A is now available since February 2016 given a two year record whereas the DTU15MSS is an average of altimetry from 1993-2012 with an averaging median year in 2003. Hence, recent models for sea level changes must be introduced in order to account for 14 years of sea level changes which can regionally contribute with a signal on the decimeter scale. Similarly the first data from the Sentinel 3B data along its interleaved orbit with Sentinel 3A is presented upon availability.

Detailed coastal evaluation of the Mean sea surface models in the North Sea and Danish waters are performed by using both Sentinel-3 data from RADS but also DTU retracked 20 Hz Sentinel 3 data to study the impact of SAR altimetry on Mean sea surface determination and determination of short wavelength coastal signals which is likely better determined using SAR altimetry than with conventional altimetry which is the base for most current mean sea surfaces.

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The Contribution of DTU17 Marine Gravity for the Arctic Bathymetry Prediction

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The Arctic Ocean is a challenging region, because of its complex and not well-documented bathymetry, together combined with the intermittent presence of sea ice and the fact that the in situ tidal observations are sparse at such high latitudes. The existing bathymetry map of the Arctic is purely derived from the sparse ship sounding data, particularly on latitudes higher than 81° (e.g. IBCAOv3). The gaps (or data holes) are filled by extrapolation and somehow inaccurate. Smith&Sandwell combined the ship sounding data with bathymetry predicted from gravity up to latitude 81° to fill the gaps. However, on even higher latitudes, the gravity to bathymetry prediction is not ever tried due to the lack of high resolution (e.g. altimetry derived) marine gravity maps. As part of the ESA CryoSat Plus for Oceans (CP4O) project, the Arctic bathymetry will be predicted from the DTU17 marine gravity, which showed massive improvement compared to the previous models (e.g. DTU15) in the Arctic.

The aim of this work is to demonstrate the contribution of marine gravity for the bathymetry prediction in the Arctic. With this presentation, the methodology to develop the gravity to bathymetry prediction will be presented. Due to the presence of thick sediments on the seafloor, the gravity and seafloor topography correlation is not significant in some areas. Such areas will be flagged and the accuracy of the predicted bathymetry will be evaluated.

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REAPER Re-Scoped: Updated Orbit Solutions for the Full ERS-1 and ERS-2 Mission Periods

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New orbit solutions for the ERS-1 and ERS-2 satellites are provided as an update to the solutions generated in the framework of the REAPER project (Reprocessing of Altimeter Products for ERS, funded by the European Space Agency-ESA). The new solutions are consistent with the GDR-E standards adopted for current altimeter satellites. In addition, the new solutions cover the full mission period for ERS-2, i.e. the period from June 2003 to July 2011 is taken into account as well. The latter results in ERS-1 and ERS-2 orbit solutions that cover, respectively, August 1991-July 1996 and May 1995-July 2011. The final orbit solutions are a combination of two orbit solutions by PosiTim UG (Germany) and Delft University of Technology (The Netherlands), using a combination of Satellite Laser Tracking (SLR) and altimeter crossover observations, augmented with Precise Range and Range-Rate Equipment (PRARE) tracking observations when available. The quality of the orbit solutions is assessed by comparing the individual orbit solutions with each other, orbit overlap analysis, fit of tracking and altimeter crossover observations, and sea level records.

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Reprocessing of TOPEX/Poseidon Precise Orbits in the CNES GDR-F Standards

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During 13 years, from its launch in 1992 to the end of 2005, the TOPEX/Poseidon (T/P) mission monitored the mean sea level with a precision of a few centimeters. The newer altimetry satellites allowed its measurement precision to be improved through cross-calibration and orbit reprocessing with more precise dynamical and correction models. This study presents the results of the first CNES reprocessing of the T/P orbits with the GDR-F standards using DORIS and SLR measurements.

This standard uses updated implementations of the ITRF2014 for the computation of the DORIS and SLR station coordinates (DPOD2014 and SLRF2014). In addition, the time variable gravity field model is updated with the measurement time series from GRACE, combined with a mascon model for the beginning of the mission (when GRACE was not yet launched). Finally, this standard uses new estimations for the geocenter motion with a new IERS linear mean pole. This study also explores the orbit improvements obtained by introducing SLR data while estimating a range bias for each SLR pass.

To assess the quality of this reprocessing, the orbits are compared to those from the NASA/Goddard Spaceflight Center, through the computation of crossover residuals and geographically correlated orbit differences.

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Improved GNSS Phase Maps in Flight Modelling and Identification, Application on Jason-2 and Jason-3.

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The OSTM/Jason-2 and Jason-3 missions are the altimetry reference missions dedicated to mapping ocean-surface topography. As such, the overall orbit accuracy is a prerequisite for the exploitation of their measurements. For this purpose, the two spacecraft carry onboard tracking instruments for precise orbit determination (POD), including a GPS receiver. The accuracy of the models used for measurement modelling is a source of systematic errors. Indeed, the actual location of the antenna phase center and its fluctuations with respect to the direction of the received signal need to be accurately known.

The current practice is to estimate the phase center offset (PCO) simultaneously in orbit with the other parameters (dynamic modelling, phase ambiguities). The phase center variations (PCV) are then obtained by residuals stacking, in an iterative process (orbit determination > residuals stacking map > orbit determination > ...). The drawback of this approach is that the PCV model may still absorb some low degree variations not correctly represented by the initial PCO adjusting, and in this case the PCO/PCV map is not correct. There are also observability issues: due to the PCV construction process, a globally unobservable parameter may be observed using the two-step iterative procedure.

Thus, a new PCO/PCV model construction method has been developed using Zernike polynomials. The initial model is a parametric model (11 parameters) adjusted simultaneously with the other orbit and measurement parameters. Depending on the attitude law, some components are clearly not observable. This model represents the low-frequency patterns. A correction is then determined from the in-flight residuals to retrieve the remaining high-frequency patterns which are well decoupled from the other model parameters. This method was applied to estimate the phase maps for the Jason-2 and Jason-3 GPS antennas. They were validated on reduced-dynamic GDR-F orbit solutions and compared to the pre-launch or in orbit phase maps provided by JPL. We finally analyze the post-fit GPS phase residuals, independent SLR residuals and induced orbit differences.

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First Orbit Determination Results for Sentinel-3B

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Sentinel-3B, the twin satellite of Sentinel-3A, is planned to be launched in April 2018. During commissioning phase the radar altimeter satellite will fly in tandem (30 sec apart) with Sentinel-3A. This is mainly done for calibration and validation of the SAR altimeter instrument.

The commissioning phase of Sentinel-3B and thus the tandem flight with Sentinel-3A will also be used to do several tests with the GPS receivers on-board Sentinel-3B. Both GPS receivers will run in parallel with the main one in the same configuration as the main receiver on Sentinel-3A and with the redundant one in different configurations to test the GPS L2C capability.

First Sentinel-3B orbit results are presented from the Copernicus POD (Precise Orbit Determination) Service. Sentinel-3B is the sixth satellite being processed by the CPOD Service, which is part of the Copernicus PDGS of the Sentinel-1, -2, and -3 missions. The nominal orbit determination procedures (Near Real Time (NRT), Short Time Critical (STC), and Non-Time Critical (NTC)) for Sentinel-3B are set up in the same way as for Sentinel-3A. The accuracies are compared to the corresponding accuracies achieved for the twin satellite.

Comparisons to independent orbit solutions from CNES and from the Copernicus POD Quality Working Group are shown as well as validation based on SLR measurements and DORIS–derived orbits. Additionally, results of the specific investigations based on the different Sentinel-3B GPS receiver configurations are presented.

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Latest Results From the Geomed2 Project: Geoid and the DOT in the Mediterranean Area

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The main aim of the Geomed2 project was the estimation of the best possible geoid approximation, given the available marine gravity data, for the wider Mediterranean area, i.e. in the area bounded between 30 < < 48 -10 < < 40, on a 2' 2' geographical grid.

For the geoid estimation, all available shipborne gravity data have been collected, edited, homogenized and used to derive the most homogeneous possible dataset in order to devise a gravimetric only geoid model. In that respect, special attention has been paid to the data debiasing, where both area-wise and track-wise methods have been employed. The geoid estimation was based on the well-known remove-compute-restore method, employing different approaches for the actual geoid modeling. The latter refer to the use of least squares collocation, Fast-collocation, 1dFFT and 2dFFT employing the original Wong&Gore modified Stokes kernel, and finally the KTH. The available gravity data have been gridded on a regular 2' 2' grid in the computation area employing ordinary krigging, serving both as input to the geoid estimation methodologies and as a project deliverable to be disseminated as a new approximation of the gravity field over the Mediterranean. When required, the low frequency components of the gravity field have been modeled using EIGEN-6c4 to d/o 1000 and different methods for RTC reduction have been tested.

The estimated geoids have then been compared with altimeter data to obtain different estimates of the Mean Dynamic Topography (MDT), which in turn allowed the definition of the currents pattern in the Mediterranean Sea. We present the advantages and pitfalls of each processing step, discussing the possible sources of noise and errors, while finally devising a final optimal estimate to be used for geodetic and oceanographic applications.

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The Geomed2 Combined Geoid Model

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The GEOMED 2 project computed a high-accuracy and resolution marine geoid model based on the availability of improved models for gravity, thanks to GRACE and GOCE in particular, for land topography and bathymetry, and the compilation of a cleaned-up and de-biased gravity database of the Mediterranean area based on BGI and SHOM data. Land and marine gravity data, the latest combined GOCE/GRACE based Global Geopotential Models and a combination of MISTRALS, EMODnet and SRTM/bathymetry terrain models were used in the gravimetric geoid computation. Computation of a gravimetric marine geoid of the Mediterranean is challenging due to:

- The poor coverage of the marine gravity data for certain areas;
- The inhomogeneous quality of the marine gravity data (bias, precision);
- The data reduction is not as efficient as achieved over land.

Marine gravity data is not available for large parts of the Mediterranean and consequently the gravimetric geoid solution is significantly less accurate there. Gravity inferred from altimetry data, or a mean sea surface corrected for mean dynamic topography (i.e., an 'oceanographic' geoid model), can be used to fill the gaps. However, ocean dynamic signal may contaminate the derived gravity or geoid, which is why a pure gravimetric solution is preferred in an ideal world.

The effect on the geoid solution of using several altimeter-based datasets, such as DTU10, DTU15 and UCSD V24 gravity, using simple gap filling, weighted combinations with the gravimetric data, and combination through collocation, will be evaluated and quantified. The combined models are compared with the gravimetric geoid solution as well as with the oceanographic geoid. The (local) errors and increased uncertainty due to the data gaps, and the subsequent effect on the ocean mean dynamic topography and geostrophic currents, can be estimated via the results of all comparisons. All models are equally compared to drifter-inferred current velocities, which constitutes an independent quality evaluation. This type of evaluation leads to a very detailed quality assessment of the models, notably as a function of spatial scale.

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Orbit Validation of Sentinel-3 Mission

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Sentinel-3A is in orbit since two years now and the precise orbit determination (POD) is well established. The official orbit solutions from CNES and the Copernicus POD Service as well as other orbit solutions from several institutes, in particular from the members of the Copernicus POD QWG (Quality Working Group), are available. The orbit solutions are derived from different software packages, are based on different models, arc lengths and parametrizations, and are computed with different observables. Some solutions are based on GPS observations only, some on DORIS observations only, and others are combined solutions. SLR measurements are mainly used for validation but might also be used in a combined orbit determination.

Correct knowledge of the antenna and reflector offsets is fundamental to guarantee the required radial orbit accuracy of 2-3 cm for the analysis of the radar altimeter measurements. The three observation techniques available on Sentinel-3A offer the opportunity to compare and validate the offsets of the SLR reflector and the GPS and DORIS antennas against each other. Offset estimates are available from different groups and from different approaches. Validation of these offsets is done based on the analysis of the manifold orbit solutions using original and updated coordinates.

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Generating Precise and Homogeneous Orbits for ESA's Altimetry Missions: ERS-1, ERS-2, Envisat, Cryosat-2, and Sentinel-3A.

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Driven by the Copernicus and GGOS (Global Geodetic Observing System) initiatives the user community has a strong demand for high-quality altimetry products. In order to derive such high-quality altimetry products precise orbits for the altimetry satellites are needed. Satellite altimetry missions meanwhile span over more than 25 years, in which our understanding of the Earth has increased significantly. As also the models used for orbit determination have improved, the satellite orbits of the altimetry satellites are not available in a uniform reference system. Homogeneously determined orbits referring to the same global reference system are, however, needed to improve our understanding of the Earth system.

The Navigation Support Office at ESA/ESOC provides precise orbits for all of ESA's altimeter missions: ERS-1, ERS-2, Envisat, Cryosat-2 and Sentinel-3A. In 2008 (and again in 2018) ESA initiated the re-processing of the altimetry data of ERS-1, ERS-2 (REAPER), including the reprocessing of the orbit determination for these satellites. But also, the other altimetry satellites, as Cryosat-2, Envisat and Sentinel-3A, benefit from re-processing. The Navigation Support Office has with its NAPEOS software package the capability to process all three satellite geodetic tracking techniques (SLR, DORIS and GNSS). Therefore, we are in the unique position to do orbit determination by combining different types of data, and by using one single software system for different satellites, which matches the most recent improvements in orbit and observation modeling and IERS conventions. Thus, we are able to generate a homogeneous set of precise orbits referring to the same reference frame for the various altimetry missions. Furthermore, we are able to quickly re-process all solution allowing us to continuously upgrade the various solutions for all satellites.

This presentation focuses on the latest results from the re-processing efforts carried out by ESA/ESOC for the generation of precise and homogeneous orbits for ERS-1, ERS-2, Envisat, Cryosat-2, and Sentinel-3A. For ERS-1 and ERS-2 SLR data are combined with altimeter data whereas for Envisat and Cryosat-2 DORIS and SLR data are combined, and for Sentinel-3A GPS observations are used in addition to DORIS and SLR. We will present the orbit determination results and evaluate the orbit accuracy by comparing our orbits with external orbits generated by other analysis centers and will highlight some of the improvements obtained from our most recent upgrades.

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Jason-3 and Sentinel-3A GPS Processing Using Zero-Difference Integer Ambiguity Fixing

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In the past, it was proven that for Jason-1 GNSS data, GPS ambiguities could be fixed, however, that was not possible on OSTM/Jason-2 because the phase measurements were not constructed with integer-valued ambiguities due to a low signal-to-noise ratio (half-cycle ambiguities only). Thus the current CNES GPS-based solutions on Jason-2 use floating ambiguities. This has been reconducted for the beginning of the missions of Jason-3 and Sentinel-3A . For HY-2A, even if the measurements have full cycle ambiguities, an operational solution with ambiguity fixing has not yet been developed, as it was not necessary to achieve the radial orbit accuracy requirement.

However, on Jason-3, the receiver behaviour is excellent, and an ambiguity fixing solution has been developed at CNES. This is a zero-difference ambiguity approach, using specific biases and phase clocks provided by the CNES/CLS IGS analysis center (grg solution).

These new orbits lead to significant improvements in the radial performance (the high-elevation SLR residuals on the core network change from 10 mm to 7 mm rms between floating and fixed solutions).

For Sentinel-3A, a recent evolution in the telemetry ground processing now allows phase measurements with integer ambiguities. A similar solution as for Jason-3 is currently under development.

This presentation will summarize the different steps of this processing, and some specific dynamic or measurement characteristics which were observed (biases, systematic errors).

A comparison between the orbits obtained in the current solutions and the new solutions will also be presented.

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Precise Orbit Determination of the Sentinel Sattelites with Gipsy-Oasis

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The Sentinel family of earth-observation satellites, part of the joint EC-ESA Copernicus programme, have been launched since 2014 and currently 7 satellites are in orbit. Besides the official orbit solutions from CNES and the Copernicus Precise Orbit Determination (POD) service, orbit (validation) solutions are also generated by the members of the Copernicus QWG (Quality Working Group). All these solutions are derived using different scientific software packages. TU Delft already has a long-established track record in POD using e.g. the GEODYN (NASA) and GHOST (DLR) software. Recently also JPL's legacy GIPSY-OASIS software has been set up for analyzing the Sentinel GPS data.

The GIPSY-OASIS software has been successfully used by JPL for POD of the Jason 1, 2 and 3 satellites and TUDelft is currently using it for POD of the Sentinel 1, 2 and 3 satellite pairs. GIPSY provides the user with a variety of models and parameterization options, including spacecraft manoeuvre, data gap handling and carrier phase ambiguity resolution. First results for Sentinel-3A indicate, based on both internal and external (satellite laser ranging (SLR)) comparisons, that a 3D root-mean-square (RMS) accuracy of 8-10 mm is achievable. Additional altimeter crossover analyses will be performed for Sentinel-3A and possibly also with 3B after it has entered its operational service. Furthermore, the effect of different force models, data gaps, manoeuvre handling and ambiguity resolution will be investigated.

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Global River Monitoring from Satellite Radar Altimetry-Achievements and Challenges

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With 25 years of observation from a range of satellite altimeters with different designs and tracking systems, an impressive array of time series has been assembled over the earth's major river and lake systems. The advent of SAR altimetry offers additional measurement possibilities, the first glimpse with CryoSat-2 now being realised by the operational Sentinel-3 mission with 2 satellites in tandem and 2 successors to ensure continuity. River systems present particular challenges; as in-situ gauges on these vital water transport systems are lost, altimetry plays an increasingly key role, despite the non-optimal spatio-temporal sampling patterns of current and past missions.

Full assessment of Sentinel-3 river monitoring capability awaits accumulation of sufficient data fully to characterise the temporal variation in target response (> 3 years). However, the results can be put in context and first assessments made of retrieval capability by comparing with prior mission outcomes.

This paper presents results from analysis of a global database of over 86,000 graded river and lake time series from Ku band altimeters, including ERS-2, Envisat, Jason-1, Jason-2 and TOPEX/Poseidon. All data were processed through an augmented system based on the ESA River and Lake system [1] and incorporating a variety of detailed regional river masks. These results are supplemented by CryoSat-2 target analysis outcomes over multiple river basins [2], and compared with Sentinel-3 target responses.

Two aspects were considered in this global study: the temporal stability of target response characteristics and the presence of climate signals. Firstly, river basins were characterised to determine accessibility of river systems to altimeter monitoring. This grading was compared with results from CryoSat-2 SAR and LRM modes, and initial analysis outcomes from Sentinel-3. One aim was to determine which parts of river systems are dominated by climate signals, yielding good 'virtual gauge stations' for incorporation into river system models. Summarising the conclusions to date: retrieving echoes from river targets in varying terrain is the primary challenge, with prior missions ERS-2 and Envisat performing well. Selection of echoes using detailed river masks improves river time series retrieval but a more generic mask is shown to be relevant where the river course is interrupted by sandbanks and islands. Here a detailed mask is not always the best option unless a co-temporal dynamic mask is generated from other remote sensed data. Waveform analysis is found to be the single most important factor in consistent height retrieval; the addition of sub-waveform editing is beneficial. Enhanced SAR processing is helpful and increased along-track sampling frequency is very significant.

With enhanced capabilities from the new generation of satellite radar altimeters, the future for river monitoring, by satellite altimetry, looks bright.

1 Salloway, M. et al., 2012. Global Inland Water Monitoring in Near Real Time: Current Capabilities. Proceedings of the 20 Years of Progress in Radar Altimetry Symposium, Venice, 24–29 September 2012, ESA SP-710. http://dx.doi.org/10.5270/esa.sp-710.altimetry2012.

2 Berry, P.A.M. & Balmbra, R., 2016. Inland water height retrieval – from Cryosat2 to Sentinel3. Proc. 'Living Planet Symposium 2016', Prague, Czech Republic, 9–13 May 2016 (ESA SP-740, August 2016)

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Constructing High-Frequency Time Series of Global Lake and Reservoir Storage Changes Using Landsat Imagery and Radar Altimetry

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High-resolution monitoring of lake and reservoir water storage is crucial for assessing global water availability in the context of changing climate and growing population. However, the spatial and temporal dynamics in inland waterbody storage is poorly monitored at a global scale because of limited in-situ measurements and observation challenges in satellites. Combining fine resolution optical imagery with level measurements by satellite altimetry has a potential to accurately deduce lake/reservoir storage variations. But existing approaches could not well capture seasonal fluctuations of global inland water storage over time due to atmospheric interference in imagery and inadequate coverage in altimetry. To address this gap, this study leveraged all archival Landsat images, including those with cloud covers, and radar altimetry to produce near monthly storage records for about 200 major lakes and reservoirs across the continental surface during the past two decades. Different from previous approaches, the proposed lake mapping method could uncover lake areas in cloudy imagery, thus improving temporal frequency of Landsat-based lake areas. Produced lake areas will then be integrated with radar altimetry levels to estimate storage changes in the studied lakes/reservoirs. The results show that our lake volume estimate outperforms existing approaches in terms of accuracy and temporal frequency. The patterns of estimated global lake/reservoir water storage changes are also analyzed and discussed

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HYDROWEB/HYSOPE: A Processing Center for Lakes and Rivers Observation

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Rivers and lakes are a key component of the continental hydrological cycle. The storage and amount and dynamic of water stored in lakes, reservoir and wetlands globally is known only crudely. Over rivers, surface water stage and slope are a key measurement for derivation of streamflow. Although river discharge and lake water storage are critical elements of land surface hydrology, they are poorly observed globally. Freely available stream gauge networks cover only a few river basins. They record water surface elevation at fixed points along river channels. Since the beginning of the 1990s, numerous in-situ networks have declined or stopped working, because of political and economic factors.

Lakes are also a fundamental component of the climate system that needed to be monitored with different variables including water level, water extent and water storage changes. Indeed these variables are considered as essential climate variables for the two first ones, and they are often not measured from in situ data or not released to a wide scientific community. Hydrolare data center hosted by the State Institute of hydrology of St Petersbourg is gathering such data from in situ, while Hydroweb is aiming to do the same from satellite altimetry and imagery.

Since the mid-nineties, satellite radar altimetry has been a successful technique for monitoring height variations of continental surface water, such as lakes and rivers. Hydroweb was developed at Legos (France) in 2003 in order to produce water level variations on large lakes and some virtual stations on the biggest rivers on the Earth. In 2016 a new database (http://hydroweb.theia-land.fr) has been developped jointly with Legos, CNES and CLS aiming at providing the time series of water level and volume calculated from the historical altimetry data and at continuously updating them with the current (Jason-3 & Sentinel-3A) and future (Sentinel-3B, Jaspon-CS, and ultimately SWOT) altimetry mission. It now produces and delivers river level data from satellite altimetry on 1470 virtual stations spread over about 20 river basins worldwide. It also provides lakes level variations for 160 lakes. A goal of the development of the new Hydroweb database is to make the availability of the products operationnal and in near real time as much as possible. A tool, named Hysope, running in CLS, is now calculating the water level on 248 virtual stations, using Jason-3 and Sentinel-3A, and on 64 lakes in an automatic mode and in NRT (the data are processed 1.5 days after their acquisition). In paralel, for almost 80 lakes, using satellite images, the ara and the volume changes are also produced in Hydroweb. Lake data are also now hosted in the Hydrolare data center.

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Long-Term Chronicles of Fluvial Characteristics and Hydraulic Variables Using Multimission Satellite Altimetry in the Congo River Basin

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In many tropical and subtropical basins, including the second largest hydrological basin in the world, the Congo River basin, the ground observation network has been discontinued and critical information on the water cycle components is no more available. In this context, satellite altimetry proved to be a powerful source of alternative information for inferring stages, discharges,

depths and water surface slope in these ungauged basins. However, the succession of altimetry missions do not provide a unique framework but instead separate solutions that must be put together.

In this study, we build a distributed set of stage-discharge rating curves using water surface elevation (WSE) from SARAL and Jason-2 satellite altimetry missions and discharges simulated through the MGB-IPH model forced with the GPM TAPEER precipitation estimates in the overlapping period. At crossovers or when the virtual stations are close enough, we were able to concatenate past and present satellite altimetry WSE observations. We obtained long-term time series of stages and discharges with a temporal sampling of at least one every 10 days and at almost a hundred of VSs spread on more than 50 rivers throughout the basin

These long-term chronicles can provide a new insight on climate change impacts at local and regional scales in the Congo River basin. Also, they are a crucial input for reducing uncertainties on freshwater contribution to the mean sea level rise.

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Ice Cover of Eurasian Lakes from Satellite and in Situ Observations

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Eurasian lakes are an integrator of climate processes and an indicator of existing or potential climate changes. Variability of ice and snow regime is important for their physical, chemical and biological properties, and for human activity (navigation, transport, fisheries, tourism etc).

We present studies of ice and snow cover of the lakes Baikal, Ladoga, Onega and Hovsgol using synergy of simultaneous active and passive satellite microwave radar altimetry observations (TOPEX/Poseidon, GFO, Jason-1, -2 and -3, ENVISAT, SARAL/Altika). An ice discrimination approach is presented and evolution of ice conditions from historical data and satellite observations is analysed. We present results of our field studies on lakes Ladoga, Onega, Baikal (Russia) and Hovsgol (Mongolia) and their relation with radar altimetry observations, optical satellite imagery and hyperspectral UAV imagery. We also address the formation of giant (diameter 5-7 km) ice rings in lakes Baikal and Hovsgol. We analyse the timing of and duration of their existence as well as associated ice and water column structure.

This research was supported by the Swiss-Russian multidisciplinary project "Lake Ladoga: Life under ice", ERA.NET RUS Plus S&T #226 "ERALECC", CNES TOSCA "LakeIce", RFBR-RGO 17-05-41043-RGO-a, Toulouse Arctic Initiative and IDEX InHERA projects.

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HYDROLARE – Main Tasks and Activity

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International Data Centre on the Hydrology of Lakes and Reservoirs (HYDROLARE) was established in 2009 by ROSHYDROMAT at the State Hydrological Institute in order to:

- develop and regularly update an international database on hydrological regime of lake and reservoirs;

- stimulate the development of the global monitoring system on lakes and reservoirs for rational use, preservation and management of their water resources

- to improve the knowledge of lateral fluxes transformation within lakes and reservoirs;

- to supply data for scientific and educational purposes, modelling, development of different global and regional projects/programmes.

Main activities of HYDROLARE are as follows:

– collection of data, further formation and maintenance of the database;

– Website management, development of the technology for monitoring database content on the Website using Google maps;

– development of cooperation with the Laboratory of Study of Geophysics and Oceanography from Space (Legos) at the National Centre for Space Research (CNES, France);

– review and correction of the climate indicator for ECV Lakes under GCOS programme;

– regularly organizing of HYDROLARE Steering Committee meetings, preparation of annual newsletter and others.

As a result of HYDROLARE/Legos cooperation a set of water level satellite altimetry data was delivered by LEGOS to HYDROLARE. Today, the HYDROLARE database except in-situ observations contains satellite data for 58 water bodies in 32 countries.

Development of the IT infrastructure provided an opportunity for upload of a new types of data (water temperature, maximum ice depth) to HYDROLARE database. Information about availability of these data in the database is displayed on the website of the centre.

A significant event for HYDROLARE in 2017 was the sixth meeting of its Steering Committee (18 to 20 July 2017, St. Petersburg, Russia).

In the presentation many others directions of HYDROLARE activity will be reflected.

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Challenges of Water Level Monitoring Over Narrow Rivers Using Multi-Mission Satellite Altimetry: Case Studies of Karun and Nile

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Given the significant reduction in the number of in situ gauge stations, satellite altimetry has become an inevitable choice for monitoring inland water bodies. There is, however, a limited literature on deriving water height from altimetry data over narrow rivers.

One of the challenges in using altimetry over inland water bodies is the heterogeneity of the radar reflections inside the altimeter footprint which results in contaminated waveforms and, consequently, inaccurate water height estimation. In case of narrow rivers, defining an appropriate water mask to exclude such outliers is a challenging task. The other source of complexity is the poor spatial and temporal data coverage which makes it difficult to conduct time series analysis, particularly along narrow rivers. Some studies use multi-mission satellite altimetry to enhance the spatiotemporal sampling over such regions. In order to do so, it is necessary that inter-satellite biases, which are also dependent on the characteristics of the study area, are estimated and compensated for.

In view of all that has been mentioned so far, we will focus on water level monitoring using data from different altimetry missions over two rivers: Karun (Iran) and Nile (Sudan). The accuracy of the extracted time series will be validated against in situ measurements provided by local authorities. The study is being conducted as part of research project SaWaM (Seasonal Water Resource Management: Regionalized Global Data and Transfer to Practice) whose main goal is the performance analysis of global hydro-meteorological data as decision support for the regional water management in semi-arid regions. SaWaM is sponsored by the Federal Ministry of Education and Research in the frame of the research initiative Global Resource Water (GRoW).

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Assessment of Non-Stationary River Runoff in Boreal Catchments with Multi-Mission Altimetry

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Changes in freshwater influx to the Arctic Ocean play a key role in driving regional dynamics and sea level change. The resulting low-salinity surface waters lead to a strong halocline in the Arctic. This stratification largely shields the cool polar surface water and sea ice from the warmer waters of Atlantic origin below and, hence, inhibits vertical fluxes of heat, salt and nutrients.

One important component of the freshwater budget is continental runoff. The hydrological regime of river runoff appears to be non-stationary, exhibiting both interannual variability and a significantly positive trend since the 1970s. Moreover, it can be shown that the Arctic ocean dynamics are sensitive to inter-annually varying river discharge.

The observational record of discharge into the Arctic Ocean, however, is still too sparse to address important science questions about the long-term behavior and development of Arctic sea level and climate. Given the insufficient monitoring from in situ gauge networks, and without any scope of improvement, satellite-based Earth observation is an important alternative, due to global coverage and homogeneous accuracy. Especially satellite altimetry and gravimetry have demonstrated their potential as an alternative to in situ measurements.

In this contribution we estimate river runoff for different boreal catchments like Mackenzie and Ob from water level time series using multi-mission altimetry data. The focus is thereby given on the estimation of non-stationary runoff using altimetric water level time series along each river, the correct interpretation of snow- and ice- reflected waveforms as well as on achieving long time series of runoff with a monthly to weekly temporal resolution.

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Lake and River Water Level Measurements from Radar and ICESat Laser Altimetry and Comparisons with GRACE

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Thanks to a quarter of a century of radar altimetry measurements from TOPEX/POSSEIDON, Jason 1, 2 and 3, ENVISAT and others, 18 measurement campaigns of the Ice, Cloud and Land Elevation Satellite (ICESat) laser altimeter over its 6 years of operations, water levels of major lakes and rivers can be remotely measured regularly with unprecedented precision, facilitating monitoring of continental water storage variations. To complement the long term record of observations from radar altimeters, laser altimeters like ICESat, sampling with smaller footprints, are well suited to retrieve water level variations of small inland water bodies and provide valuable data at river crossings. Individual laser water returns height measurements can be better discriminated from those from land or vegetation by careful examination of the laser waveforms characteristics, and using available imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) and other sensors. Derived water height estimates for lakes in South America from radar and laser altimetry measurements are compared and validated using available in situ datasets. Estimating the surface extent from available imagery, and deriving corresponding estimates of volume variations for each water body, those can be compared with mass variations from time-variable gravity measurements from 15 years of Gravity Recovery And Climate Experiment (GRACE) observations. We use the latest one-degree global iterated mascon solution from GSFC, transformed into volume changes by assuming a constant density.

In addition, expanding on our validation of radar altimetry observations of river height measuremnets using our record of laser altimetry observations from ICESat along the Yukon River, we explore the altimetric record for the Chena River, a 100-mile (160 km) tributary of the Tanana River in the Interior region of the U.S. state of Alaska. It flows generally west from the White Mountains to the Tanana River near the city of Fairbanks, which empties into the Yukon.

These methods will demonstrate the power of using combined remote sensing observations to monitor water resources and facilitate their management. Upcoming laser altimetry mission data, with increased coverage, improved sampling, like ICESat-2 and GEDI, precise measurements and innovative processing techniques, including inland water products specifically formulated for these applications, will provide valuable data to combine with SWOT, and GRACE-follow on mission data, to help address the need for continuous monitoring of continental water storage variations from space measurements

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Extending the Database of Hydrology Targets for DEM Onboard Altimeters

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Satellite radar altimetry has been used to measure river and lake water levels with large successes for the last 20 years. However, the altimeters, being designed to observe the oceans, can have some difficulties to track the surface of other water bodies especially in cases where the surrounding topography is rugged. To overcome this issue, recent radar altimeters (on Jason-3 and Sentinel-3) can be operated in two tracking modes: the classic Close Loop (CL) mode and the Open Loop (OL) mode. In OL mode the position of the tracking window is not defined autonomously by the altimeter but is calculated using internal tables that are built from a database of hydrology targets. This database provides the position and approximate elevation of the water bodies. The necessary accuracy of the average elevation is around ± 10 meters.

Such a database has been recently enhanced for Jason-3 with more than 4500 targets worldwide. The results of its use have been documented in open literature and during the last OSTST meeting. Usually, the Jason altimeter tracks water for about 50 % of the overpasses when operated in CL mode. This percentage increases to more than 90 % when OL mode is used. For some rivers the results can be more dramatic. For example, some medium-sized rivers of width between 150 and 250 meters have been observed for the first time by the Jason altimeters when Jason 3 was in OL with very good data quality when compared to independent in situ data. Overall, there is a large increase of the number of accurate water height measurements when the OL mode is used.

Given the relevance for the user community, we have extended the coverage and the density of this database for Jason-3, Sentinel-3A and Sentinel-3B. Two global, high resolution water masks (derived from optical and microwave measurements) allow us to define the position of the targets. The number of targets for Sentinel-3 is about 10 times the number of targets for Jason-3. A first guess of the altitudes is provided by a global DEM. For their validation, we use different strategies for rivers and for lakes.

The river heights are validated using the profile along the river course which is computed from a combination of DEM data and altimetry. A global river network has been processed to achieve this goal.

The lake heights are validated using the Cryosat-2 data over more than 4500 lakes and 500 reservoirs worldwide (among them 2000 over north America and 1000 over Asia). Time series have been processed using 5 years of data (2010-2014) and a database of polygons for both lakes (GLWD) and reservoirs (GRanD).

We present the new global database, the expected improvements for spatial hydrology, some methods we have used to build it and difficulties we had to overcome. We also present results of validation on Sentinel-3A and Jason3 measurements.

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Identification of the Rybinsk Reservoir Ice Cover and Investigation of its Interannual Variability Based on Satellite Altimetry and Radiometry

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The article presents the results of ice cover identification and the investigation of interannual ice regime variability of the Rybinsk Reservoir based on the satellite altimetry and radiometry data. For this purpose, the study analyzed the joint distribution of the radio brightness temperature of the underlying surface, measured by two channels (18.7 and 34.0 GHz) with an on-board microwave radiometer, and the backscattering coefficient at the Ku frequency calculated by the altimeter. The analysis of the joint distribution of these parameters identified two areas of the cluster that corresponded to pure water and ice accumulation. The study was carried out using the topological filtering algorithm DPS (Discrete Perfect Sets) and subsequent isolation of the most massive 3-D condensations. Verification of these areas was carried out according to a series of images in the visible range of the MODIS multi-channel spectroradiometers, installed on the Terra and Aqua satellites, the study also relies on ENVISAT satellite MERIS spectrometer data and the spectrometer data of Landsat series of satellites.

The results of the research showed that this approach allows us to identify with adequate accuracy the ice cover in the water area of the Rybinsk Reservoir. According to Jason-1 and Jason-2 satellite data, from 2002 to 2016, the time for the start of freezing shifted at a rate of 0.624 ± 0.152 days per year, and the opening time amounted to 0.673 ± 0.256 days per year. The duration of the ice regime for this time interval decreased at a rate of -1.303 ± 0.341 days per year. The maximum duration of freezing was observed in the winter of 2002/2003 and amounted to 164 days, and the minimum - in the winter of 2006/2007 and was 134 days..

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G-REALM: Investigating the Jason-3 and Sentinel-3A Data Sets for the Next Phase of Operational Lake and Wetland Monitoring

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G-REALM is a NASA/USDA funded operational program offering water-level products for lakes and reservoirs that are currently derived from the NASA/CNES TOPEX/Jason series of radar altimeters. The main stakeholder is the USDA/Foreign Agricultural Service, though many other end-users utilize the products for a variety of interdisciplinary science and operational programs. The products are additionally delivered to NASA PO.DAAC archive for the MEaSUREs Earth Science Data Records (ESDR) Program. There is an increasing demand for a more global monitoring service that in particular captures the variations in the smallest (1 to 100 km²) reservoirs and water holdings in arid and semi-arid regions. Here, water resources are critical to both agriculture and regional security. There is also a demand for surface water level products across wetland zones in respect of inland fisheries and assessments of catch potential.

Recent efforts to increase the number of monitored lakes, and to extend the TOPEX/Jason time series to achieve a 25yr observation set for Climate/Earth Record considerations, has shown that great care needs to be taken with respect to the merger of results from multiple instrument platforms, and with respect to the varying location of the satellite overpasses. Effort has also been focused on the creation of products from the Sentinel-3A mission, and on merging the results with the SARAL/ENVISAT/ERS archive. Noting here that all three missions, Jason-3, Sentinel-3A and Sentinel-3B will be utilized for the delivery of operational products for the USDA Decisions Support System.

In 2018 the G-REALM team will also be expanding the current G-REALM system and offering a suite of test-case products to gauge end-user response. These include elements of lake extent, bathymetry, and storage, and also wetland water level variations for fisheries and ecology applications. The application of hydrological modelling i.e. the prediction of water levels/extents in the absence of altimetric observations will also be tested. Although not as efficient as direct water level observation, preliminary studies have shown that these methods offer a secondary "inferred" water level product that can be used to highlight from seasonal and inter-annual variability to trends and inter-decadal changes

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The SEOM "Sentinel-3 Hydrologic Altimetry Processor PrototypE" (SHAPE) Project: Progresses & Status

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The SHAPE project, started in September 2015, is part of SEOM, Scientific Exploitation of Operational Missions, an ESA program element which aims at expanding the international research community, strengthening the leadership of the European EO research community and addressing new scientific researches.

This Research and Development intends to make the best use of SAR (delay-Doppler) altimetry data for applications in hydrology. The study focuses on three main variables of interest: river water level (RWL), river discharge (RWD) and lake water level (LWL), which are part of the Terrestrial Essential Climate Variables (TECV) defined by GCOS.

The works started with CryoSat-2 data (before the launch of Sentinel-3A) and is progressively integrating Sentinel-3A as another input for the SHAPE processor.

The project has developed its own modular and fully configurable altimetric processor comprising a delay-Doppler processor (from L1A to L1b), a L2 processor including state-of-the-art geophysical corrections and new SARM retrackers. On top of this, the SHAPE project also implements its own L3 processor (from L2 to RWL and LWL) and L4 processors (from RWL to RWD) and a validation and verification framework. With the confidence brought by the validation and verification steps, the project implements hydrological dynamic and semi-distributed models of river catchments able to assimilate RWL measurements in order to estimate RWD.

The high level of configuration of the processor allows to work in parallel on two different baselines. The first one is dedicated to mimic as much as possible the real Sentinel-3 baseline and the second a baseline optimised for hydrology, at all processing levels.

The project focuses on 3 rivers (Amazon, Danube and Brahmaputra) and 2 lakes (Vänern and Titicaca). Sentinel-3A L1A data is considered to be used on the Brahmaputra river while CryoSat-2 L1A data is used on the other water bodies.

In this communication, we report both on the progresses made by the project as well as providing results, we also report about its status and planning

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Validation of 25 Years of Altimetry Data over Inland Water: from T/P to Sentinel-3A

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Exploring the potential of radar altimetry for the monitoring of inland waters has been a continuous challenge since the launch of Topex/Poseidon in 1992. Research efforts to develop the potential of radar altimetry over inland waters addressed three main directions: (1) improve accuracy and reprocess water level measurement (mainly through the improvement of retracking algorithms and atmospheric corrections) ; (2) develop hydrological applications (river leveling, water storage estimate, flood tracking and river modeling) ; (3) contribute to the design of new satellite missions better fitted to hydrology requirements and providing higher along-track resolution.

A standardised approach is needed in order to assess the quality of alti-hydrology river water level measurements and ease its assimilation into models. This means on one hand to quantify the accuracy of radar altimetry measurements (comparison with reference in situ data), and on the other hand to estimate the uncertainty of radar altimetry measurements. This is not yet a common practice in the community.

We present here a standard method that has been developed to assess the products quality (vertical accuracy and temporal sampling loss rate (TSLR) of the resulting water level time series) and to estimate individual measurements uncertainty. It relies on a statistical characterisation of the deviation between radar altimetry measurements and in situ data.

Compared to the validation methodology presented during the 20YPRA Symposium, the methodology has been modified and extended to cope with non-strictly repeat orbits such as drifting orbits (SARAL, etc.) and geodesic orbits (CryoSat-2).

The method has been applied to a wide extent of existing data bases (ESA, CNES/AVISO, CTOH, HydroWeb, River & Lake, etc.) as well as products from past & on-going research projects (CASH, PISTACH, SHAPE, ACA-DDP/DeDop). It has been implemented in the frame of CNES technical studies (R&T) to assess the performances of new 1D (CLS, 2010) and 2D retracking algorithms (Along-Track, 2018). The altimetry missions that are included in this study encompasses T/P, ESR-2, ENVISAT, Jason-2, CryoSat-2, SARAL/AltiKa, Jason-3 and Sentinel-3A

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Selective Retracking of Bright Targets Exploiting Consecutive Waveforms: Application to LRM Altimetry over Rivers

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The progresses made in LRM Alti-Hydrology during the past 25 years have been largely achieved thanks to the development and improvement of the retracking techniques. In the case of inland water, the retracking step is by far the most critical in retrieving the water levels of rivers and lakes.

Numerous studies have focused on developing and improving 1D retracking algorithms, which process waveforms separately. Despite the very interesting results obtained by some 1D retrackers (e.g., Ice3, SAMOSA), they somehow miss the information provided by consecutive waveforms. Indeed, they retrack each waveform independently of the neighbor waveforms.

Among other limitations are the following underlying hypotheses such as : the observed scene is dominated by only one reflector and/or we want to retrack one dominating reflector and/or the algorithm in use is intrinsically limited to retrack one dominating reflector per waveform.

In this paper, we introduce a new approach to exploit the information contained in consecutive waveforms that are properly aligned, i.e., the range-chronogram (RCG). We call such an approach a "2D retracker" in opposition the algorithms discussed above that we call "1D retrackers".

Our work is based on the detection of hyperbolic signatures (HS) from within the RCG, because such a signature is the natural response of bright target as seen by a moving altimeter. More precisely, we are interested in finding the point of closest approach (POCA) associated to each hyperbolic signature and thus to each bright reflector.

After the precise (range, azimuth) coordinates of the "POCA of interest" have been computed, we run a dedicated 1D retracker that is able to retrack the response of few (K) dominating reflectors per waveform (typically k=3).

The processor can run different core algorithms to detect POCA coordinates in any RCG. It has many pre/post-processing options including pre-filtering of the RCG, estimating the equivalent number of looks (similarly as in SARM), etc.

Such a 2D retracker has some usual properties among which:

- Only the records from the RCG for which a POCA has been detected are processed, this avoids to waste CPU cycles ;

- Each record might be affected more than one epoch (retracked) value.

As such, we end up with records having from 0 to K range values ;

Examples and validation results over a few test cases will be presented along with comparison to 1D retrackers such as Ice1.

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Monitoring Inland Water Bodies from Sentinel-3 and CryoSat-2 SAR Altimeters

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Abstract

Due to environmental effect of climate changes and human activities, monitoring inland water bodies, from satellite radar altimetry, is nowadays significantly important. New generation of satellite altimetry missions, i.e. CryoSat-2 and Sentinel-3, are worthy of being used in this major. Monitoring inland water bodies is not a main objective for the both missions. However due to their facility, they can be used to study inland water bodies.

In this study, the performance of CryoSat-2 SAR mode and Sentinel-3 in monitoring lake water level variation is being evaluated via SAR sub-waveform retracking. To end this, L1b and L2 data of both missions are analyzed over Derg lake in Ireland and Vanern lake in Sweden.

Sub-waveform retracking, as an effective retracking method to monitor inland water bodies, provides an RMS of about 10 cm for Vanern lake and 13 cm for Derg lake, compared with in-situ gauge data, for both missions. This analysis will continue over more lakes with different shapes and sizes in different climate zones to arrive an optimized evaluation of the performance of these two missions.

Keywords: Inland water bodies, SAR altimeter, sub-waveform, retracking algorithm

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Influence of the Recent Climatic Events on the Surface Water Storage of the Tonle Sap

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Lakes and reservoirs have been identified as sentinels of climate change. The Tonle Sap Lake is the largest lake in the Mekong Basin and in South East Asia and, due to the importance of its ecosystem, it is has been described as the “heart of the lower Mekong”. Its functioning depends on the annual flood pulse governed by the flow of the Mekong River. This study reports an analysis of the impact of the recent climatic events, from El Niño 1997/1998 to El Niño 2015/2016, on surface storage variations in the Tonle Sap watershed determined by combining remotely sensed observations multispectral images and radar altimetry from 1993 to 2016. Surface water volume variations are highly correlated with rainy season rainfall in the Mekong River Basin (R=0.84) at interannual time-scale. Extreme droughts and floods are observed when deficits and excesses of rainfall are recorded in both the Tonle Sap watershed and the Mekong River Basin during moderate to very strong El Niño/La Niña events (R=-0.70) enhanced by the Pacific Decadal Oscillation (R=-0.68). An almost equal influence of Indian and Western North Pacific Monsoons was identified. The below normal vegetation activity was observed during the first semester of 2016 as a consequence of the extreme drought of 2015.

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Calibration and Validation of Inland Waters Heights from SAR, SARIN and Conventional Altimetry

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Altimetry has progressed from conventional ku band nadir pointing single pulse systems to ka band on SARAL-AltiKa, SAR on CryoSat-2 and Sentinel-3 and SARin also on Cryosat-2. These altimeters have provided a wealth of data over oceans, ice and inland waters. A major difficulty is identifying the presence of the inland water within the radar footprint as off-pointing can produce inaccurate water heights. Techniques to identify the water reflectors include a river mask and inspection of the resultant waveform. The interferometric SARin mode of CryoSat-2 has the capability to provide an estimate of the cross-angle allowing an improved height correction for off-pointing. In this paper we seek to quantify the improvement in inland water heights associated with developments in altimeter architecture as well as investigating the generic tropospheric correction. Most altimetric satellites carry a microwave radiometer for the tropospheric correction over oceans but the instrument becomes saturated by returns over land with the tropospheric correction typically inferred from a numerical weather model (e.g. ECMWF). Model validation can be undertaken through comparison against the total zenith delay estimated from processing of Global Navigation Satellite Systems (GNSS) data from ground receivers close to the satellite ground track. However, due to logistics many areas are not covered by a GNSS receiver network. Utilising data from the

Amazon GNSS network, Brazil, we will attempt to quantify the error in the tropospheric measurement from numerical weather models. To assess the enhancements due to altimeter architecture we will use inland water heights from ERS-2, Jason, Envisat, SARAL-AltiKa, OSTM, CryoSat-2 and Sentinel-3 over the Amazon Basin and elsewhere (e.g. the Mekong). Over the Amazon CryoSat-2 operated in its SAR and SARin mode. Results will be shown of the improvement enabled by correcting for off-pointing in the CryoSat-2 SARin data as the ground track crosses a meandering river. Calibration of the inland water heights will utilise stage heights from river gauges. For repeat pass missions calibration is relatively straightforward but for non-repeat missions such as CryoSat-2 a correction for river slope is required as the river crossing points can span over 100 km either side of the gauge. The results will show the advantage of the ka altimeter on SARAL-AltiKa, although spurious measurements exist probably due to rain, and the preference of SAR altimeters over the conventional altimeters

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Satellite Altimetry for Discharge Estimation and for Monitoring Extreme Events

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In view of recent dramatic floods and drought events, detection of trends in the frequency and magnitude of long time series of flood data is of scientific interest and practical importance. It is essential in many fields, from climate change impact assessment to water resources management, from flood forecasting to drought monitoring, for the planning of future water resources and flood protection systems. In these fields, the system design is traditionally based on the assumption of stationarity in hydrological processes such as river water level or discharge, usually obtained from traditional monitoring network measuring water level, river flow velocity and cross section geometry. The lack of long continuous observed time series, due to actual decreasing of the number of sensors across the world and to the cost of installation and maintenance of the monitoring network, prevent to identify trends over large areas. The most direct method of deriving such information on a global scale involves satellite earth observation. Over the last two decades, the growing availability of satellite sensors, and the results so far obtained in the estimation of river discharge from the monitoring of the water level through satellite radar altimetry has fostered the interest on this subject.

In this study, satellite altimetry water level data are used to set-up a consistent, continuous and up-to-date daily discharge dataset for different sites across the world. Satellite-derived water levels are related to river discharge data available over overlapping time spans to estimate empirical rating curves. Once validated, the rating curves are used to fill and extrapolate discharge data over the whole period of altimetry water level observations. The long continuous discharge time series so obtained have allowed to perform a trend analysis on extreme flood and drought events. Specifically, annual maximum discharge and peak-over threshold values are extracted from the simulated daily discharge time series, as proxy variables of independent flood events. Moreover, the threshold level approach is considered to discriminate between low/moderate flow regimes and to identify hydrological drought events.

For flood and drought events, a trend analysis is also carried out to identify changes in the frequency and magnitude of extreme events through the Mann-Kendall (M-K) test and a linear regression model between time and the flood magnitude.

The analysis has permitted to identify areas of the world prone to floods and drought, so that appropriate actions for disaster risk mitigation, and continuous improvement in disaster preparedness, response, and recovery practices can be adopted.

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Sentinel3 in the Context of Multisensor Synergy: New Discovery and Analysis Tools

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The fully operational Ocean Sentinel-1-2-3 constellation provides a wide range of viewpoints to the ocean surface from the coast to the open ocean, at various scales and from physical to biological processes. Discovering this huge heterogeneous dataset (in the wider context of complementary datasets) in a simple, fast and yet convenient way is now possible using intuitive visualization tools, available as web or standalone applications developed in the frame of the Ocean Virtual Laboratory project. Today, these tools are widely used by the scientific community to better exploit sensor synergy to understand and monitor oceanic processes. For instance, the visualization of near real time data from Sentinel-3 sensors (SLSTR, OLCI and SRAL) on the whole planet and only a few hours after acquisition is just a few clicks away thanks to the S3View web portal.

A collection of use cases will be demonstrated to illustrate the functionalities of these tools:

- Collocating Sentinel-1 and Sentinel-3 data and comparing them with Chlorophyll and Sea Surface Temperature images from OLCI and SLSTR enables to detect oceanic fronts and eddies, highlighting strong and energetic ocean currents.

- Displaying radar data from SRAL at 20 Hz and comparing them with Sun glitter images from OLCI enables to analyse high resolution dynamical signal such as internal waves.

- Overlapping Sentinel-1-2-3 helps to assess ocean wave modification by surface currents.

- Finally, analyzing SRAL along track observations collocated with SLSTR or OLCI enables to better analyse possible sources of atmospheric or sea ice contamination.

Interactive demo of the tools will also be available on the OceanDataLab booth. Online tools are available at https://ovl.oceandatalab.com and https://s3view.oceandatalab.com

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On the Potential of Altimetry Data for the Calibration of Hydraulic Models: a Comparison of Different Products and Multi-Mission Series

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The calibration of hydraulic models is typically based on in-situ data. However, high costs of maintenance of monitoring networks and survey campaigns lead to a continuous decreasing of gauging stations. To this end, spaceborne approaches represent a viable alternative source of data. However, despite the growing availability of satellite altimetry data and their use in many hydrological and hydraulic applications, the potential of altimetry data for the calibration of hydraulic model is still to explore. This study investigates the performances of different altimetry series for calibrating a quasi-2d model built with detailed topographic information. The model refers to a 140 km-stretch of Po River, where traditionally observed data are available. The remotely sensed data used for this test are collected by different missions (i.e., ERS-2, ENVISAT, SARAL/Altika, Topex-Poseidon and Jason-2) by investigating the effect of (i) record length (i.e. number of satellite measurements provided by a given sensor at a specific satellite track) and (ii) data uncertainty (i.e. altimetry measurements errors). Since the relatively poor time resolution of satellites constrains the operational use of altimetric time series, in this study we also investigate the use of multi-mission altimetry series obtained by merging datasets sensed by different sensors over the study area. Benefits of the highest temporal frequency of multi-mission series are tested by calibrating the quasi-2d model referring in turn to original satellite series and multi-mission datasets. Results highlight that, for all datasets, longer record lengths lead to lower uncertainty on the identification of the Manning's coefficient, with mean absolute errors that range from 0.2 m up to 0.7 m in terms of water surface elevation, in relation to the considered altimetry product. In case of frequent and accurate satellite data (i.e. Jason-2), the multi-mission series seem unable to provide additional benefits in calibrating the hydraulic model. On the other hand, multi-mission series outperform low frequency products (i.e. ENVISAT) when the latter are available only for short period (i.e., shorter than 3 years). Overall, this study provides a comprehensive comparison of altimetry data and multi-mission altimetry series, and sheds some lights on their potential use for hydraulic modelling

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Evaluating the Use of River Level Estimations Derived From Radar Altimetry Data into Hydrological Modelling of the Chari River Basin

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Radar altimetry data is now widely employed across different hydrological applications. As an example the data acquired from radar altimeters can be used to estimate the level of water bodies such as rivers, lakes, reservoirs and flood plains, which is essential for environmental monitoring and natural resource management. The benefit of this Remote Sensing technique would be essential over poor in situ data environments to track natural phenomena and to derive critical information in an economical and sustainable manner.

In this case study, an application of a remote sensing technique is presented for height detection of large inland rivers by using Sentinel-3 Synthetic Aperture Radar Altimeter (SRAL) data. This work is aimed at evaluating the use of Radar Altimetry data to enable a systematic ingestion of satellite-based river level estimations into flood monitoring and forecasting systems developed for poorly-gauged river basins.

The study area consists of the southern portion of the Chad Basin with a particular focus for Logone and Chari rivers. Since 2015 UNITAR-UNOSAT has been working on developing, with the support of CIMA Foundation, an integrated flood forecasting routine ('Flood Finder Chad') over this portion of Chad to enable flood awareness and rapid mapping services for humanitarian assistance purposes. The modelling chain is essentially composed of a hydrological routine and a dedicated 1D flood model, which are able to cover most vulnerable areas along the two rivers. The Hydrological Model is forced with satellite-derived precipitation products and numerical weather prediction outputs. Output rainfall runoff results are calibrated by using in situ river level measurements. River stage at gauging stations are collected in the field by 'Ministère de l'Eau et de l'Assainissement du Tchad' staff.

In this context and with the objective to increase the number of river level estimations along Chari and Logone rivers, an extraction of height estimations by radar altimetry is proposed. This will be accomplished starting from the identification, based on Sentinel-3A ground tracks, of virtual stations along the rivers. The on-demand exploitation of Sentinel-3 SRAL L1A data products in SAR mode (high-resolution) over these targets will be then achieved through the use of a web processing service, based on the SARvatore (SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation) Processor Prototype, within ESA's G-POD (Grid-Processing On Demand) distributed computing platform.

A first validation of altimetry-based water level will be performed through a comparison with gauge records of Logone and Chari rivers from 2016 and 2017 rainy seasons. After that an evaluation of hydro-modelling results, before and after a model calibration based on radar altimetry data, is expected to be done.

The aim of this activity is to complement field observations across a poorly-gauged basin such as the one of Chari River. An expected advantage of using such approach is to better evaluate hydrological modelling outputs along the river network in order to improve short-term forecast average discharge. Outcomes from this case study will be used to evaluate a possible integration of High-Resolution Radar Altimetry data into this system.

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Adaptation of the SAR Altimetric Ocean Retracker for Inland Waters: Methodology and Preliminary Results

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Due to the relatively recent advance towards SAR altimetry operation, started by ESA CryoSat-2 mission and continued with the future SAR Sentinel-3 and Sentinel-6 missions, most of the studies over in-land water are quite limited to the classical LRM operation.

When trying to retrack waveforms over continental water bodies, the radar altimetric community has widely applied the threshold, Ice-1 (OCOG) and Ice-2 retrackers. The evolution towards SAR altimetry operation opens a new paradigm for the radar altimeter capabilities in general and for continental water monitoring in particular (thanks to the improved along-track resolution). Ocean-like waveforms and specular-like waveforms can be found in in-land SAR operation, but also some more complex and heterogeneous responses with multiple peaks are observed due to the off-nadir land contamination.

Taking into account such heterogeneity of the backscattered echoes, a model flexible and adaptable to these shapes is required. Investigations done by isardSAT [Martin-Puig, et al. 2013] have shown that the [Ray et al., 2015], devoted to retrack ocean waveform shapes, could also fit specular-like shapes over lakes. On top of this, some studies also showed the capacity of this model to fit lead-like waveforms [Jain et al. 2014].

The core of this poster is to describe the adaptation and formulation of the in-house isardSAT implementation of the SAR ocean retracker to in-land operation. The inclusion of an additional fitting parameter related to the surface roughness (mean-squared slopes) allows to flexibly adapt to more specular-like responses as well as to Ocea-like. Multiple peak detection or totally distorted waveforms will be difficult to retrack with a model like [Ray et al., 2015]. Some pre-processing stage is required to choose the proper portion of the waveform related to the surface beneath the track: DEM supported retracking operation will be exploited in this case. A initial validation of this adapted retracker will be carried out with SAR data from CryoSat-2 and Sentinel-3 data over specific regions of interest, like Ebre river (and lakes) or Amazonas river.

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Integrating Sentinel Series Data to Monitor Lake Level Variation in Tibet

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In response to the current global warming episode, most of lakes over the Tibetan Plateau have increased arguably owing to an accelerating melt of alpine glaciers and permafrost. This phenomenon has been observed in the past few decades from satellite altimetry and local gauges. However, the spatiotemporal characteristic of altimetry mission's frozen ground tracks is one of major limitations in the coverage of lakes over TP. Hence, many of them were only checked by ICESat mission whose ground tracks were much denser. Also, the intermission bias between radar altimetry satellites, such as Envisat, Jason series, SARAL/AltiKa, and Sentinel-3 is another concern while adjusting the discrete time series. In this study, we use Sentinel-1/-2 imaging satellite and a digital elevation model (DEM) to recover the historical water level variation of several lakes on TP, by using the Thematic Imagery-Altimetry System (TIAS) approach. This method utilizes waterline positions from classified water bodies in each image and calculates geoidal heights from a co-registered DEM. The lake level information is further compared with Envisat, SARAL/AltiKa, Jason series, and Sentinel-3 altimetry measurements to estimate relative accuracy. We will demonstrate an extended altimetric time series and to fully explore the potential of integrating all Sentinel missions in terrestrial water studies

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Can Sentinel Measure Water Level over Po River at 80HZ?

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The SAR Radar Altimeter (SRAL) onboard Sentinel-3, the new operational satellite built and launched by ESA for the European Copernicus Programme, is extremely promising to measure inland water level (and eventually, river discharge) at global scale, pushing the measurements to narrow rivers (200-300 m). The SAR Altimeter technology is supposed to offer better performances than those of conventional altimeters due to the high along-track resolution that may enable high-resolution (90 meters) measurements of water level transects across rivers. Moreover, the constellation of more satellites (Sentinel-3A and the next Sentinel-3B) will provide improved global coverage. In view of the advances on the accuracy and the spatial resolution (inter-track 52 km) of the altimetric measurements (much better with respect to Envisat altimetry), we are interested in the evaluation of the precision and accuracy of the measurements in SAR mode, especially, on the estimation of inland water level for small rivers.

In this analysis, we used Sentinel-3 SAR processing adapted to inland water (SAMOSA+) at 80 Hz. The very high resolution used corresponds to a single burst and seems to be the most appropriate frequency to exploit the unfocused processing of the SAR mode. The ESA G-POD Service, SARvatore (SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation) for CryoSat-2 & Sentinel-3 is used to process remotely and on-demand CryoSat-2 SAR/SARin & Sentinel-3 SAR data, from L1a (FBR) data products until SAR/SARin Level-2 geophysical data products (https://gpod.eo.esa.int/services/SENTINEL3_SAR/).

The validation and the accuracy of the Sentinel-3 SAR mode is assessed along the Po River, exploiting the extensive number of ground stations available. Looking at previous results, a comparison against data from past and current satellite altimeters is carried out also for underlying the advances of the SAR technology with respect to the traditional technology.

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Lake Bracciano Water Level Variation from Sentinel-3 Measurements Processed at the GPOD SARvatore Service

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Lake Bracciano is a lake of volcanic origin located in the Italian region of Lazio 32 km northwest of Rome. It is one of the major lakes of Italy and has a circular perimeter of approximately 32 km. Its inflow is from precipitation only as there are no inflowing rivers. As the lake serves as a drinking water reservoir for the city of Rome, it has been under control since 1986 to avoid the pollution of its waters. For this reason, Bracciano is among the cleanest lakes of Italy. The absence of motorized navigation favors sailing, canoeing and swimming.

The Sentinel-3A satellite, successfully launched on 16 February 2016, carries the SAR Altimeter (SRAL). SRAL is the main topographic instrument and is expected to provide accurate topography measurements over sea ice, ice sheets, rivers and lakes. It operates in dual frequency mode (Ku and C bands) and is supported by a microwave radiometer for atmospheric correction and a DORIS receiver for orbit positioning. Sentinel-3A overflies the lake collecting data every month (27 days).

According to in-situ measurements, the Lake Bracciano water level has significantly decreased between March and December 2017. Therefore, considering the 27-day repeat period of Sentinel-3, water level variations detected by the SRAL altimeter can be regularly compared to in-situ measurements to infer the performance of the instrument over such a very small lake.

In this study, Sentinel-3 products made available by the ESA GPOD SARvatore for Sentinel-3 online and on-demand processing service (https://gpod.eo.esa.int/services/SENTINEL3_SAR) have been generated and analysed. The SARvatore service exploits the computational power provided by ESA Grid Processing on Demand system (GPOD) that is a generic GRID-based operational computing environment where specific data-handling Earth-Observation services can be seamlessly plugged-in. One of the goals of GPOD is to provide users with a fast computing facility without the need to handle bulky data.

SARvatore for S3 Products have been processed in SAR mode at 20 Hz (330 m along-track resolution) and 80 Hz (83 m) and retracked with the advanced inland water SAMOSA+ retracker. Results obtained have been compared to official Sentinel-3 inland water products including water level estimates from physical and empirical retrackers.

Considering the signal degradation recorded in L1b waveforms (multiple-peaks), well known criteria have been adopted to correctly filter the data improving the quality of the estimates.

Future works will aim at improving the SAR processing by properly selecting the waveforms composing the stack before multi-looking (e.g. as successfully done in the ESA-funded CRUCIAL Project, research.ncl.ac.uk/crucial). Following the launch of the Sentinel-3B satellite in April 2018, the possibility to select additional water bodies at Sentinel-3 A/B crossovers will be investigated.

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25 Years of Radar Altimetry over the Antarctic Ice Shelves: Retrieving Trends and Variability

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The main limitation in predicting future sea-level rise lies in our inability to project changes in the rate of ice flow from land to ocean. This difficulty is mostly due to an incomplete understanding of climate/ice-sheet feedbacks and the nonlinear response of the ice sheet to changes in the fringing ice shelves. In Antarctica, many of these floating ice shelves restrain (through resistive stresses) the flow of ice from inland drainage basins towards the ocean. When an ice shelf thins and/or weakens, its ability to "buttress" Antarctica's ice discharge is reduced. Satellite observations over the past two decades have shown that the main Antarctic sectors losing mass (e.g. the Amundsen Sea, Bellingshausen Sea, and Antarctic Peninsula) are associated with rapidly thinning ice shelves, which in turn have been linked to changes in oceanic and atmospheric circulation. To understand these linkages and the relation to changes in global climate we need long and continuous observational records; which are limited particularly in the polar regions. Continuous data from overlapping satellite altimetry missions over the past 25+ years provides a unique opportunity to retrieve not only long-term (climate-related) trends in ice-shelf change, but also to analyze the variability of these systems on interannual-to-decadal timescales; something that was made possible only recently with the extended and uninterrupted altimetry record. To achieve this, we must first overcome some technical challenges associated with the complex altimetry measurement over icy surfaces, and the differences between the various altimeter systems. Here, we summarize some results on changes in ice-shelf height and mass during the past 25 years as seen by satellite altimeters. We discuss the improvements and limitations on the synthesis of heterogeneous satellite altimetry data and derived height-change and basal melt-rate estimates over the Antarctic ice shelves. We also show results from our current effort towards providing the community with a >25-year homogeneous ice-shelf height-change product at the finest temporal scale and spatial resolution allowed by the data.

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Pysiral – An Open Source PYthon Sea Ice Radar ALtimetry Toolbox

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pysiral is an open source toolbox, which has been developed at the Alfred Wegener Institute for the task of creating the sea ice thickness climate data record in the ESA Climate Change Initiative on Sea Ice. It is designed as a unified processing tools for primary (Level-1 radar altimeter) data with a flexible algorithm configuration system to retrieve consistent freeboard and thickness from different radar altimeter missions with the same code base. The workflow of pysiral consists of 4 separate tools:

1. Level-1 Pre-processing: (input harmonization, regional sub setting, orbit merging)

2. Level-2 Processor: Along-track freeboard & thickness with uncertainties and auxiliary parameters

3. Level-2 Pre-Processor: Generation of daily Level-2 data collections

4. Level-3 Processor: Generation of Level-3 (gridded) products

All algorithm components including surface type classification, retracking and freeboard to thickness conversion are implemented as python classes that are easily selectable in configuration files for both algorithm stability and rapid prototyping. In addition, all algorithm modules are meant for standalone use in external tools and are not bound to the main pysiral tool chain. The pysiral output module also creates products based on templates that are fully compliant with the Climate & Forecast netCDF conventions.

Since its initial development for ESA CCI, pysiral has been used in several other initiatives (AWI CryoSat-2 sea ice product, EU SPICES, C3S & CMEMS) and its development is actively continued. This includes a growing choice of supported altimeter missions (ERS-1/2, Envisat, CryoSat-2, Sentinel-3A/B & ICESat) as well as a wide range of supported auxiliary products (sea ice concentration, sea ice type, snow depth). The source code can be obtained under a GNU GPLv3 license and a release on github is projected for the near future.

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Retrieving Sea Surface Topography in the Arctic Ocean from Satellite Altimetry with Ocean/Sea-Ice Processing Continuity

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Satellite altimetry was designed for open ocean, however efforts to retrieve surface topography information in ice covered areas have started back in 2004 (Peacock et al.). Recent advances in waveform processing allow for a processing continuity from open ocean to ice covered areas, and the retrieval of ocean and sea-ice topography from the same algorithm.

A dataset based on Envisat and SARAL/AltiKa missions was generated using this new waveform retracking approach, for sea surface height and sea ice freeboard.

Validation results suggest that these datasets perform relatively well compared to existing products and in-situ data, and that large scale ocean circulation features are observable. Investigation of ocean variability on long time scales in the Arctic Ocean would benefit from an Arctic oriented reprocessing of all available missions. Future challenges for ice covered areas include the development of a true multi-mission combination system, tailored to the area, to resolve small-scale features.

This approach will be used to produce future CMEMS Arctic sea level products

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Assessment of Sentinel-3 SAR Altimetry over Ice Sheets

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The first Sentinel-3 satellite was launched in 2016 and carries onboard a Ku-band Synthetic Aperture Radar (SAR) altimeter. With coverage up to a latitude of ~81.5 degrees and a repeat period of 27 days, it offers the opportunity to measure surface topography and elevation change across much of the Antarctic and Greenland Ice Sheets, therefore continuing the existing 25 year radar altimeter record. The global operation of Sentinel-3 in SAR mode differs from all past Ku-band instruments; for the first time SAR measurements are routinely acquired across the interiors of the ice sheets; however unlike CryoSat-2 it does not carry an interferometer to aid signal retrieval in regions of complex coastal terrain. In view of these differences and the novel characteristics of the Sentinel-3 system, assessments of the performance of the instrument are required, to evaluate the satellite's utility for monitoring Earth's Polar regions, and its accuracy relative to historical low resolution altimeter measurements.

Here, we analyse Sentinel-3a SAR altimetry data acquired during the first two years of routine operations. We focus both on inland ice sheet regions, where Sentinel-3 provides the first operational SAR altimeter measurements, and also on coastal areas with more complex topography. We investigate SAR waveforms and retrieved elevations in these regions to assess the impact of varying topographic regimes, and compare these observations to reference airborne altimetry, to provide an assessment of Sentinel-3 performance to date over ice sheets.

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SAR Altimetry Processing Development for Ice Sheets

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For the past 25 years, polar-orbiting satellite radar altimeters have provided a valuable record of ice sheet elevation change and mass balance. One of the principle challenges associated with radar altimetry comes from the relatively large ground footprint of conventional pulse-limited radars, which reduces their capacity to make measurements in areas of complex topographic terrain. In recent years, progress has been made towards improving ground resolution, through the implementation of Synthetic Aperture Radar (SAR), or Delay-Doppler, techniques. In 2010, the launch of CryoSat-2 heralded the start of a new era of SAR Interferometric (SARIn) altimetry. However, because the satellite operated in SARIn and LRM mode over the ice sheets, many of the non-interferometric SAR altimeter processing techniques have been optimized for water and sea ice surfaces only. The launch of Sentinel-3, which provides full non-interferometric SAR coverage of the ice sheets, therefore presents the opportunity to further develop these SAR processing methodologies over ice sheets, for the purpose of scientific exploitation of this operational mission.

Here we present results from SPICE (Sentinel-3 Performance Improvement for Ice Sheets), a 2 year study that has focused on developing and evaluating Sentinel-3 SAR altimetry processing methodologies over the Polar ice sheets. The project, which is funded by ESA's SEOM (Scientific Exploitation of Operational Missions) programme, has worked in advance of the operational phase of Sentinel-3, to emulate Sentinel-3 SAR and pseudo-LRM data from dedicated CryoSat-2 SAR acquisitions made at the Lake Vostok, Dome C and Spirit sites in East Antarctica, and from reprocessed SARIn data in Greenland. In Phase 1 of the project we have evaluated existing processing methodologies, and in Phase 2 we have investigated new evolutions to the L1b Delay-Doppler Processing and L2 retracking chains. In this presentation we focus on describing the novel L2 processing developments used to improve retracking over complex topographic surfaces, such as those found across the margins of the Antarctic Ice Sheet, and on evaluating these measurements using independent airborne and satellite datasets.

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Impact of Greenland Surface Melt on CryoSat-2 Elevation Measurements

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In July 2012, an unprecedented 99 % of the surface area of the Greenland ice sheet experienced melting as a result of higher than average surface temperatures, with approximately one third of the ice sheet undergoing melt for the first time in a decade. This event created a frozen melt layer near the ice sheet surface, resetting the radar scattering horizon and complicating elevation retrievals from radar altimeters. Surface melt on the Greenland ice sheet induces poorly understood changes in snowpack scattering characteristics, introducing considerable uncertainty into estimates of ice mass balance. Using a backscatter model which retrieves the depth distribution of radar backscatter from Low Resolution Mode CryoSat-2 waveforms we are able to, for the first time, map changes in radar penetration depth across the interior of the Greenland ice sheet between 2010 and 2017. As a result of the extreme melt event in the summer of 2012, we estimate a step-like reduction in penetration depth of 2 m on average at surface elevations greater than 2000 m and – due to the subsequent accumulation of snowfall on the ice sheet surface – observe a continuous increase in radar penetration depth until the end of 2017, to within approximately 50 cm of that recorded before July 2012. Such improved knowledge of changes in the radar scattering horizon have the potential to inform more accurate estimates of Greenland ice mass balance from satellite radar altimetry

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A New Digital Elevation Model of Antarctica Derived from CryoSat-2 Altimetry

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Accurate and up-to-date knowledge of Antarctic topography is required for the planning of fieldwork, numerical ice sheet modelling, and the tracking of ice motion. Here, we present a new Digital Elevation Model (DEM) of the Antarctic ice sheet and ice shelves using 6 years of elevation measurements recorded by the CryoSat-2 satellite radar altimeter between July 2010 and July 2016. The DEM is formed from spatio-temporal fits to elevation measurements accumulated within 1, 2 and 5 km grid cells, and is posted at the modal resolution of 1 km. Altogether, the extensive time series recorded by CryoSat-2 provides observations for 94 % of the grounded ice sheet and 98 % of the floating ice shelves, and the remaining grid cells North of 88° S are interpolated using ordinary kriging. We assess the accuracy of the DEM using airborne laser altimeter measurements acquired during NASA Operation IceBridge campaigns, and find a median and root mean square difference of −0.30 m and 13.50 m, respectively. The DEM uncertainty rises in regions of high slope – especially where elevation measurements were acquired in Low Resolution Mode – and, taking this into account, we estimate the average accuracy to be 9.5 m – a value that is comparable to or better than that of other models derived from satellite radar and laser altimetry.

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Techniques for Combining Multi-Mission Satellite Altimetry Time Series of Ice Sheet Elevation Change

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ESA's Climate Change Initiative aims to provide data that is critically important to the global effort to combat climate change, using long-term Earth observation archives. Surface elevation change data from altimetry is one of a suite of parameters used to characterise ice sheets, whose variations affect sea level and climate.

We present a method for combining surface elevation change data from any number of satellite-mounted radar altimeters, providing their mission periods overlap, into a single spatially regular, consistently calibrated, long-term time series dataset.

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Observation of the Ice Cover in the Okhotsk Sea by Dual-Frequency Precipitation Radar

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Orbital radars are actively used for monitoring of the ice cover in the Arctic seas. Scatterometers perform measurements at middle incidence angles and provide the largest coverage of the territory and the frequency of observation. A significant disadvantage is the low spatial resolution and hence, complexity of

measurements in the coastal area and in the inland waters. Altimeters have the better spatial resolution however the frequency of observations is not high.

The Global Precipitation Mission (GPM) satellite with on-board DPR of wavelengths of 2.2 cm and 0.8 cm has been in orbit since 2014. The Earth surface is sensed by orbital radar at small incidence angles (<18.5 degree). Its main objective is to measure the vertical precipitation profile from a height of 10 km to the Earth surface with a vertical resolution of 250 m in 245 km swath in the Ku-band and 120 km swath in the Ka-band. RCS measured at the maximal distance refers to the reflection from the Earth surface therefore the reflected signal contains information on the scattering surface.

DPR operates in the scanning mode in the direction perpendicular to the satellite track (49 cells). The beam width is about 0.7 degree and a footprint size is about 5 km. Radar cross section (RCS) measured at the maximum distance corresponds to the surface backscattering and therefore can be used for retrieval of the scattering surface parameters. However, the JAXA standard information product does not contain information about the parameters of sea waves, snow, or ice cover obtained from DPR data.

Our team has experience in the processing of DPR data of the sea surface and has developed algorithms for retrieval of the mean square slopes of large-scale waves and near surface wind speed. We have started using DPR data to study the inland water scattering covered by ice on the example of Lake Baikal.

In this research a sea ice in the Okhotsk sea in 2015-2016 winter season was investigated. Data processing has shown, that at small incidence angles the RCS of sea ice is higher than RCS of land therefore ice can be detected. Dependence of RCS on the incidence angle was calculated. It was shown that dependence of RCS on incidence angle differ for open water and ice cover. This feature permitted to determine the type of scattering surface and to detect the formation and destruction of ice cover using in the algorithm the angular dependences. Air temperature influences on the dielectric properties of sea ice and it opens possibility to select situation of dry ice with negative temperature and wet ice at positive temperature.

Comparison radar images with Modis and SAR images confirmed suggesting that it is possible to observe the separate floe and RCS depends from relation between open water and ice cover in the radar footprint.

The first results show that DPR is new instrument for monitor of sea ice and researches will be continued. Interesting results can be achieved if combine altimeter and DPR data.

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Inter-Comparison of AltiKa and CryoSat Over Greenland

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Radar altimetry has been successfully used for more than 25 years to study the ice sheets as well as estimate their volume change and contribution to sea level rise. However, one of the remaining sources of uncertainty in radar altimetry lies in the penetration of the radar wave into the snowpack. Indeed, all the altimeters in space are operating at Ku-band (13.6 GHz) but the penetration depth at this frequency has been estimated to be around 5 to 7 m below the actual ice sheet surface and could introduce a potential bias in elevation retrievals from radar altimetry. The issue of the penetration of the radar signal is complex as it is dependent on the surface properties (surface melt, snow density, presence of ice layers, ice grain size) and is thus both temporally and spatially variable. AltiKa, on board SARAL, launched in February 2013 is the first space-borne altimeter using Ka-band (37 GHz), a frequency almost 3 times higher than Ku-band with an expected reduced penetration depth of 0.1 to 0.3 m below the actual surface. Using AltiKa in combination with CryoSat, operating since 2010, offers the opportunity to use measurements acquired at Ka and Ku-band over a coincident time period. In this study, we estimate the scattering horizon of Ka and Ku-band radar altimetry by assessing the difference between AltiKa and CryoSat satellite observations. For this purpose, we use a crossover analysis over Greenland with a focus on the EGIG line study area, where in-situ and airborne measurements were collected as part of the ESA CryoVEx campaigns conducted in Fall 2016 and Spring 2017. We implemented three different retrackers, OCOG, TCOG and TFMRA, in order to assess their relative sensitivity to waveform shape. Across the EGIG area, AltiKa retrieves a higher elevation than CryoSat with all three retrackers, which is expected due to the shorter wavelength resulting in a lower penetration depth. The mean Ka/Ku crossover elevation difference is 1.66 m, 1.63 m and 1.57 m for the OCOG, TCOG and TFMRA retrackers respectively, with corresponding standard deviations of 0.88 m, 0.55 m and 0.80 m. The crossover difference increases with decreasing elevation across the study area, and there is no clear seasonal variability depicted in this crossover analysis. Surface elevation change over Greenland has also been computed using a plane fit method and reveals a very good agreement between AltiKa and CryoSat rates of elevation change. Unlike on elevation, the penetration depth difference does not affect the rates of elevation change

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Radar Altimetry to Support Ice Navigation

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The Finnish Meteorological Institute provides estimates of Polar Code Risk Index Outcomes (RIO), as well as radar freeboard (rfb) and sea ice thickness (SIT) based on Cryosat-2 NRT L1b data. RIO is a variable representing the risk of a ship getting damaged by sea ice. The methodology is based on a kNN classification of waveform characteristics taught with RIO estimates from operational ice charts. Basis of the production system is the PySiral software package, originally developed in Alfred Wegener Institute as part of the ESA CCI sea ice project.

We shall present the current state of our online product, as well as as the technical implementation. We will present the first results of the system application into Sentinel-3 data, and the difficulties faced due to the inconsistencies between CS-2 and S3 SAR processing.

We will also consider the overall usability of CS-2 and S3 data in support of tactical navigation. Due to current NRT timeliness of CS-2 (2 days) and the sparse spatial sampling, use of CS-2 data for ice charting is limited. Ways to combine altimeter along track estimates to S1A/B SAR) data to mitigate the limitations of spatial sampling will be demonstrated. Finally, the potential gain of time critical (~ 2h) radar altimeter data will be assessed. Even with current setup (timeliness and coverage) of CS-2, its data has applications in ship and operation planning.

We will also present examples of RIO analyses for different ship classes, meant to meet with the demands of creating a Polar Code compliant a ship operational manual. That is, a map of average ice conditions as well as an estimate of most severe conditions to be met in the planned operations area. As a side product we shall also present time series analysis of RIO for the CS-2 period along the Northern Sea Route, showing considerable inter-annual variation.

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ERS-2, EnviSat, AltiKa: 23 Years of Repeat Radar Altimetry above the Antarctica Ice Sheet

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Since 1995, ERS-2 and EnviSat have flight on the same 35-days repeat orbit providing a very dense coverage of the Antarctic ice sheet. We developed an along-track processing to extract elevation time series every kilometer along track. This processing algorithm takes into account the poor orbit repeatitivity and changes in snow pack properties. In 2013, the CNES and the ISRO has launched the altimeter AltiKa on SARAL, on the same 35-days repeat orbit. This altimeter works in Ka band (37 GHz) instead of Ku (13.6 GHz) as previously.

They provide an assessment of volume change at the scale of the continent with an unprecedented space and time resolution. On most of the continent, elevation changes are within ±15 cm/yr. We observe large scale variations that we interpret with the help of GRACE as variability in meteorological forcing, especially in East Antarctica. On the contrary, we observe long term trend in elevation on some fast flowing glaciers, especially in the Amundsen sea embayment. In particular, from ERS-2 to AltiKa, we observe a strong acceleration of the losses of Pine Island glacier. We will focus here on some places of interest in order to show the possibilities and limitations of radar altimetry when applied to ice sheets.

Altimetry also provide information on snpwpack characteristics. We compare the S band (3.2 Ghz) with the Ku and Ka band backscatters and explain the seasonal variations. The S-band seems to be mostly sensitive to surface roughness, while ka-band reacts with temperature. Depending on surface roughness, Ku-band follows Ka-band or S-band. Multi-frequency altimeter missions are the key for improving our understanding of the altimeter over ice sheet.

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Greenland CCI Surface Elevation Change Products from Cryosat-2 and SARAL/ALtiKa.

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A long, unbroken sequence of satellite altimetry elevation changes is an essential climate variable. Here, we present the surface elevation change (SEC) record provided in the ESA Greenland ice sheet CCI project, as 5-year running means spanning back to 1992. The 5-year running mean is chosen to show the imprint of climate change on the Greenland ice sheet surface elevation change and limits the imprint of weather variability.

We mainly focus on the novel results from ESA's Cryosat-2 and the French-Indian SARAL/ALtiKa satellite, as this latest generation of radar altimeters provides new opportunities for monitoring Greenland ice sheet SEC. The orbit of Cryosat-2 enables the generation of a higher temporal-resolution data product from Ku-band radar altimetry; a 2-year running mean SEC. This 2-year product shows the inter-annual variability in weather and its imprint in surface elevation. The observational period of SARAL/ALtiKa satellite has now matured, and an experimental SEC product from Ka-band altimetry is being provided in the Greenland ice sheet CCI. The Ka-band radar altimetry is less subject to surface penetration in firn covered areas, and map changes in snowfall in the interior region of the Greenland ice sheet.

The Greenland ice sheet CCI now provides 11 maps of Greenland SEC generated from Cryosat-2 or SARAL/ALtiKa data. All giving insight into the complex nature of the changing Greenland ice sheet. The emerging patterns from comparing both Cryosat-2 5-year vs. 2-year SEC and Ku-band vs. Ka-band SEC may relate to the interplay between the surface mass balance and internal ice sheet dynamics.

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Satellite-Derived Sea-Ice Export and Its Impact on Arctic Ice Mass Balance

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Variability of the Arctic sea-ice mass balance is determined by sea ice production and melt on the one hand, and sea ice export on the other hand. Sea ice exported through the Fram Strait also represents a significant fresh water input to the North Atlantic, which could in turn modulate the intensity of the thermohaline circulation. We present the first estimates of winter sea ice volume export through the Fram Strait using CryoSat-2 sea ice thickness retrievals and three different drift products for the years 2010 to 2017. The export rates vary between -21 and -540 km³/month. We find that ice drift variability is the main driver of annual and interannual ice volume export variability, and that the interannual variations of the ice drift are driven by large scale variability of the atmospheric circulation captured by the Arctic Oscillation and North Atlantic Oscillation indices. On shorter timescale, however, the seasonal cycle is also driven by the mean thickness of exported sea ice, typically peaking in March. Considering Arctic winter multiyear ice volume changes, 54 % of the variability can be explained by the variations of ice volume export through the Fram Strait

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Radar Wave Interaction with the Antarctica Snowpack: Outcomes of the ESA SPICE Project

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Earth's polar regions have been monitored near continuously by altimeter satellites for 30 years now. Thanks to their wide coverage and high temporal sampling, they have greatly improved our knowledge of the ice-sheet topography and our understanding of the ice sheet dynamics. Until the 2010s, radar altimeters have been exclusively operating in Ku-band, in Low Resolution Mode (LRM).

A new generation of altimeter satellites has been launched in the last few years: Cryosat-2 (2010), Saral/Altika (2013) and Sentinel-3A (2016). Thanks to its Ka frequency, the penetration depth of the AltiKa signal in the snowpack is theoretically much smaller than usual Ku frequency radars, reducing the volume scattering measured in Ku-band. This is supposed to facilitate the estimation of the ice sheet elevation at snow/air interface. On the other hand, Cryosat-2 and Sentinel-3A carry a new generation of radar altimeter, operating in the innovative "Delay Doppler" mode (or SAR mode), improving the along track resolution from several kilometers (conventional altimetry) to 300 meters.

The ESA SPICE project (Sentinel-3 Performance Improvement for Ice Sheets), has worked in advance of the operational phase of Sentinel-3 to assess SAR altimetry over the polar ice sheets, thanks to sporadic Cryosat-2 SAR acquisitions made over Antarctica and Greenland. A first task of the project consisted of evaluating and improving SAR altimetry L1/L2 processing. This poster presents achieved results of the project second task, focused on radar wave penetration through Ku/Ka bands measurements. For this purpose, the Croysat-2 products generated by the most performant algorithms developed during SPICE project are compared to LRM AltiKa acquisitions at crossovers, over the East Antarctica interior.

First, a direct comparison of Cryosat-2 and AltiKa waveforms is presented over the flat surface of lake Vostok clearly showing the different behaviors of both frequencies. Secondly, the precision and accuracy of the surface elevation estimated from the Cryosat-2 and AltiKa waveforms are compared to Digital Elevation Models. The study outcomes give essential informations about the radar altimetry sensitivity to volume scattering, not only in Ku and Ka bands, but also in LRM and SAR altimetry mode. This work is particularly instructive at that moment when a future polar observing mission has to be defined (double Ku/Ka bands Sentinel-9) and designed with the objective to monitor even more precisely the impact of global warming on polar ice-sheets.

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Validation of Satellite Cryosphere Altimetry with Airborne Surveys – Results of CryoVEx Campaigns

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In preparations for the first CryoSat mission ESA initiated a series of validations campaigns called CryoVEx – CryoSat Validation Experiment. For the first time DTU Space carried out a validation campaign in 2003 and continued in the following years with several pre-launch experiment followed by the first direct validation campaign in spring 2011 after the successful launch of CryoSat-2 in 2010. Since then validation experiments have been carried out both in the Arctic and Antarctic with different instrumental setup. The performance of CryoSat-2 has been validated using an airborne version of the SIRAL altimeter (ASIRAS, manufactured by Radar System Technology) combined with laser scanner altimeter observations together with e.g visual imagery. Also in the very recent campaigns a Ka-band radar system (KAREN) manufactured by MetaSensing has been added to the observations providing the opportunity to collect coincident dual frequency radar altimetry.

Combined with in situ observations on ground at selected validations sites, these airborne observations provide a unique dataset of observations coincident in time and space of surface elevations and elevation changes for validation of the CryoSat products. These data have been used for studies that asses the accuracy and error sources of CryoSat-2 (e.g. the CryoVal sea ice and land ice projects).

The presentation will give an overview of the airborne campaigns and summarize the main results obtained with the datasets gathered

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Topography of A68 Iceberg from Altika and Cryosat Data.

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In July 2017 a large section of 5800 km2 of the Larsen C ice shelf broke off creating the second largest iceberg on records . It was named A68 by the US National Ice Center. Since its calving, A68 slowly drifted away from the coast. We analyzed ~30 Sentinel-1 (A and B) SAR and Sentinel-3 OLCI images , using classical image processing tools to estimate the shape and area of A68 and to precisely determine the position of its centroid and its orientation.

All altimeter passes between July 2017 and January 2018 sampling A68 have also been analyzed to estimate the surface topography of the iceberg. Because A68 is located at a latitude higher than 66° no Jason (2-3) data can be used. However several Altika, HY2A, Cryosat and Sentinel-3 are available to compute the topography of A68 at high resolution. In total, more than a hundred passes are used. The position of the iceberg centroid and its orientation are used to re-map the altimeter data within the same fixed frame of reference. Assuming that the surface topography varies little during the 7 month period, the different altimeter freeboard estimates can be compared at crossover points to compute calibration coefficients (vs Cryosat). This allows to compare Ku and Ka estimates (and to get an approximation of the penetration depth of the signals). It also allows to compare SAR (Sentinel3), SARin (Cryosat) and LRM (Alitka, HY2A) height estimates.

Using the intercomparison data set we produces a high resolution (300 m) iceberg topography based on along-track range measurements. As Cryosat always operates in SAR interferometry mode over the iceberg, we also analyzed the swath elevation (across-track) measurements. This increases by a factor 100 the number of available measurements. They are then used to produce a second estimate of the HR surface topography.

These two estimates can also be merged to compute the topography and an associated error. The topography will be used as a reference to analyze in detail the future evolution of A68 in particular its fragmentation and melting.

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A Synergistic Use of Sentinel-1 and CryoSat-2 SAR Data over Sea Ice in the Cryo-SEANICE ESA project

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CryoSat-2 baseline-C SAR/SARIN Altimetry data are a very valuable asset to measure freeboard over sea ice areas. Nevertheless, in a large number of cases, the altimeter waveforms are too complex to permit a proper surface type classification and/or retracking. This is the case when multiple strong reflectors (mainly leads) are in and/or in the vicinity of the altimeter footprints (strong reflectors from the vicinity are then seen through the altimeter sidelobes). Other examples may encompass the presence of different sea ice types and snow. In order to discover more of these cases, colocated SAR imagery is the perfect companion. Only tightly codated (altimetry, imagery) pairs are used in this fast varying environment, with potentially strong surface currents and extreme events.

A dedicated tool has been assembled in the frame of the Cryo-SEANICE project funded by ESA. This tool not only superimposes the image layers (one of them being the surface type classification layer) and the projected altimeter footprint but it also provides a view on many parameters related to the current altimeter record : Waveform(s), Stack(s), RIP(s) and RIP(s) parameters, Stack(s) Peakiness as well as imagery derived statistics corresponding to the altimeter footprint content in the image. The Footprint Content Analysis Tool (FACT) provides many other features (also means to manually or automatically move the virtual location of the altimeter footprint within the image in order to refine the analysis and account for surface motion between acquisitions)not published.

The tool and some preliminary results are presented in the view of improving our understanding of the signatures found in the altimeter signals and perform some sporadic checks of the surface type parameter in the CryoSat-2 L2 products.

The potential benefits of this approach are better understand the retrackers performance in the future.

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Looking Forward and Backward: New Techniques for Quantifying Dynamic Surface-Height Changes With Radar Altimetry in Antarctica

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Observations and modeling over the past decade have shown that ice streams and outlet glaciers in Antarctica can change on timescales from minutes to millennia, which complicates the separation of internally driven, dynamic variability from externally forced secular trends. Current methods for analyzing ice-sheet change from surface-height data rely on the assumption that the time evolution of an ice-sheet surface will follow a prescribed functional form, then leverage additional datasets to identify drivers of change. Here, we test an alternate method for quantifying and analyzing ice-sheet surface-height variability, where we apply no a priori assumptions for data reduction, then employ spatial statistical methods to identify patterns of change. Using seven years (2011-2017) of CryoSat-2 synthetic aperture radar-interferometric mode altimetry data, we apply this technique to five Siple Coast ice streams (Mercer, Whillans, Kamb, Bindschadler, and MacAyeal), identify modes of surface-height variability, and attribute these characteristic spatial patterns of height-change anomalies to potential drivers. We also reassess the ability of past radar altimeters (ERS-1, ERS-2, and Envisat) to observe dynamic surface-height changes by developing a radar simulator to model surface backscatter and conducting a suite of synthetic and realistic height-change experiments. We hope to demonstrate that by taking advantage of the entire waveform of data from past missions and combining this technique with spatial statistical methods applied to modern radar altimetry, we can generate time series of dynamic height changes in Antarctica that span a quarter century, allowing for more robust identification of the drivers of ice-sheet change in Antarctica.

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Toward a CryoSat-2 / Sentinel-3 Continuum of Sea-Ice Thickness and Volume Observations

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Arctic sea-ice plays a major role on the global climate and is a key witness to the on-going climate change, which justifies the importance of closely monitoring its evolution. While sea-ice extent is available since the premises of satellite observations, its thickness and volume are still poorly known.

The quite recent SAR delay-Doppler in altimetry has brought new possibilities in sea-ice thickness estimation. The pioneer of this technic is SIRAL on-board CryoSat-2, which continuously observed the Polar Regions since 2010, providing the first sea-ice thickness time series with good accordance with in-situ measurements. The recent launch of Sentinel-3A on 16 February 2016, and the planned launch of Sentinel-3B before the end of 2018, both equipped with a SAR altimeter, promises for a long record of the sea-ice up to 81.5 degrees of latitude. Nevertheless, the continuity of the sea ice thickness with CryoSat-2 still raised some difficulties and no solution has been published yet. The Sentinel-3 and CryoSat-2 altimeters being very similar the problem most probably comes from the ground processing, which differ because of their different objectives: the CryoSat-2 Earth Explorer scientific mission is dedicated to the observation of the Polar Regions whereas the Sentinel-3 Copernicus operational missions focused on lower latitudes.

The ground processing differs at distinct steps, the main ones being the Doppler SAR processing, that provides the synthetic echoes, and the retracking, that extracts the range from the echoes. In the presented study, we have considered these two levels and analysed step by step the impacts of the different choices. For the Doppler SAR processing, two options present in the CryoSat-2 ground processing chain have been deactivated in the Sentinel-3: the hamming filtering and the zero-padding interpolation. Thanks to the configurable SARvatore processing chain running on the ESA Research and Service Support (RSS) processing platform, we have been able to analyse the impact of both of these options on the sea-ice thickness measurements and to conclude on the configuration that provides the best results. In a similar process, we have compared the effects of two retrackers belonging to two different families: TFMRA, a robust but heuristic threshold retracker, and SAMOSA+, a retracker based on a physical model that can handle the very atypical specular waveforms over oceans that are encountered over sea-ice.

For a better understanding of the effects of these various options, we have evaluated separately their impacts on the diffuse waveforms, encountered over the ice floes, and on the specular waveforms that are specific to the ones encountered over the leads (water in the sea-ice fractures).

The resulting sea-ice freeboards have been evaluated against different datasets of in-situ measurements (OIB, IMB, BGEP).

Finally, these configurations have been applied on the full December 2016 month of data over the Arctic Basin up to 81.5°N with CryoSat-2 on one hand, and Sentinel-3 on the other hand. The mean difference between the output freeboard maps is of 0.3 cm with a standard deviation of 5.4cm. The relatively high standard deviation may come from the large proportion of thin ice still present in December, and which is difficult to measure by altimetry. Other months of winter will be analysed for the final presentation, but these results already demonstrate the ability of Sentinel-3 to ensure the continuity with CryoSat-2 of the sea-ice thickness and volume observations.

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Consistent CryoSat-2 and Envisat Freeboard Retrieval of Arctic and Antarctic Sea Ice

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In order to derive long-term changes in sea-ice volume, a multi-decadal sea-ice thickness record is required. CryoSat-2 has showcased the potential of radar altimetry for sea-ice mass-balance estimation over the last years. However, precursor altimetry missions such as Envisat have not been exploited to the same extent so far. Combining both missions to acquire a decadal sea-ice volume data set requires a method to overcome the discrepancies due to different footprint sizes from either pulse-limited or beam-sharpened radar echoes. In this study, we implemented an inter-mission consistent surface-type classification scheme for both hemispheres, based on the waveform pulse peakiness, leading-edge width, and sea-ice backscatter. In order to achieve a consistent retracking procedure, we adapted the Threshold First Maximum Retracker Algorithm, previously used only for CryoSat-2, to develop an adaptive retracker threshold that depends on waveform characteristics. With our method, we produce a global and consistent freeboard data set for CryoSat-2 and Envisat. This novel data set features a maximum monthly difference in the mission-overlap period of 2.2 cm (2.7 cm) for the Arctic (Antarctic) based on all gridded values with spatial resolution of 25 km × 25 km and 50 km × 50 km for the Arctic and Antarctic, respectively.

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Polar Ocean Case Study. An Example for Dedop Studio.

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We present a case study that demonstrates a benefit of using a low-level (1BL) altimetry in SAR mode, and a newly developed Dedop studio tool, in the coastal area of Svalbard. We use Sentinel-3 L1A data, adapted from the CryoSat-2 FBR and processed by the DDP. The study combines in situ and satellite observations to improve the knowledge about the position of a narrow coastal current flowing around Svalbard

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Four Decades of Surface Elevation Change of the Antarctic Ice Sheet from Multi-Mission Satellite Altimetry

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The contribution of the Antarctic Ice Sheet to present-day sea level change still contains large uncertainties. In several regions of West Antarctica, changing ice flow leads to rapid dynamic thinning while in East Antarctica the rates are relatively small. Elevation change rates determined from a single altimetry mission are influenced by interannual variations of precipitation as well as of changes in the ice dynamics. Only a multi-mission analysis is able to extend the time interval and hence identify the long-term trend in the elevation changes. We present our approach to consistently combine the missions Seasat, Geosat, ERS-1, ERS-2, Envisat, ICESat and CryoSat-2 and hence obtain a time series of surface elevation changes from 07/1978 to 12/2017.

We show that a consistent reprocessing of ice sheet altimetry from different missions is not only a prerequisite for the combination, but also improves the precision of radar altimetry data by about 50%. We will discuss which special aspects have to be considered when combining conventional radar altimetry with the high resolution SARIn-mode data of CryoSat-2 and the high precision ICESat laser altimeter measurements. Therefore we will present a novel approach to create a joint time series. The excellent agreement with precipitation anomalies from ECMWF ERA-Interim and GIA-corrected mass anomalies from GRACE demonstrates that we successfully eliminated the inter-mission biases. The combination of the independent data sets can be used for the interpretation of the results. Our results provide an unprecedented insight into the variations of the Antarctic Ice Sheet over four decades and help to separate the long-term trends from interannual variations.

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CryoSat: ESA'S Ice Explorer Mission, 8 Years in Operations: Status, Main Achievements and Future Outlook

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CryoSat-2 was launched eight years ago, on the 8th April 2010 and it is the first European ice mission dedicated to monitoring precise changes in the thickness of polar ice sheets and floating sea ice. CryoSat-2 carries an innovative radar altimeter called the Synthetic Aperture Interferometric Altimeter (SIRAL) with two antennas and with extended capabilities to meet the measurement requirements for ice-sheets elevation and sea-ice freeboard. Results have shown that data is of high quality thanks to an altimeter that is behaving exceptional well within its design specifications.

Since its launch, CryoSat data has been used by different scientific communities on a number of Earth Science topics also beyond its prime mission objectives, cryosphere. Scope of this paper is to describe the current mission status, its achievements and provide programmatic highlights for the period 2018-2019.

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Sea Ice Mass Reconciliation Exercise (SIMRE) for Altimetry Based Sea Ice Thickness Data Sets

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Satellite radar altimetry is the primary remote sensing data source for retrieval of Arctic sea-ice thickness. Observational data sets are available from current and previous missions, namely ESA's Envisat and CryoSat as well as NASA ICESat. In addition, freeboard results have been published from the earlier ESA ERS missions and candidates for new data products are the Sentinel-3 constellation, the CNES AltiKa mission and NASA laser altimeter successor ICESat-2. With all the different aspects of sensor type and orbit configuration, all missions have unique properties. In addition, thickness retrieval algorithms have evolved over time and data centers have developed different strategies. These strategies may vary in choice of auxiliary data sets, algorithm parts and product resolution and masking.

The Sea Ice Mass Reconciliation Exercise (SIMRE) is a project by the sea-ice radar altimetry community to bridge the challenges of comparing data sets across missions and algorithms. The ESA Arctic+ research program facilitates this project with the objective to collect existing data sets and to derive a reconciled estimate of Arctic sea ice mass balance. Starting with CryoSat-2 products, we compare results from different data centers (UCL, AWI, JPL, NASA GSFC & LEGOS) at full resolution along selected orbits. In addition, three regions exemplary for pure first-year ice, multiyear ice and mixed ice condition are used to compare the difference in thickness and thickness change between products over the seasonal cycle.

We present the main results of SIMRE activities in terms of validation and impact analysis of a reconciled sea ice mass estimate. The methodology is designed to be extendible and the project is open to future expansions. Model results of sea ice thickness will be added to extend the scope of SIMRE beyond EO products.

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Towards a Multi-Decadal Pan-Arctic Snow Depth on Sea Ice: A Novel Model - Satellite - Airborne Fusion Approach.

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Only satellite remote sensing can provide the pan-Arctic view required to fully understand changes to the Earth's sea ice fields. At present, important observational gaps remain which limit both our interpretation of remote-sensing data and our understanding of the Arctic climate system. Snow on sea ice represents both a major source of uncertainty in sea ice concentration and thickness retrievals from satellite data, and a poorly resolved quantity of climatic importance. Snow representation in climate models remains poorly constrained and constitutes a severe limitation for accurate operational polar services as well as for long term accurate climate predictions. Current methods to retrieve snow depth over Arctic sea ice from satellites are limited to certain ice types or exhibit a large data gap over the pole.

We review existing snow on sea ice products from models and satellite, airborne, and in-situ measurements. We extend a recently developed dual-satellite multi-frequency (Ka/Ku) airborne calibrated approach to derive snow thickness on sea ice to a mono-frequency single satellite approach following the same calibration methodology. Using snow and radar freeboard from NASA's Operation IceBridge and ESA's Arctic spring campaigns, we calibrate radar freeboard from ESA's CryoSat-2, Envisat, AltiKa, and Sentinel-3 satellites to align them to the snow surface and snow/ice interface. Snow thickness is then estimated as the difference between the two calibrated freeboards, and improving on existing approaches that use satellite radar altimetry to measure snow depth, we achieve spatial coverage up to 88º N and temporal coverage from 2003. We demonstrate the seasonal and inter-annual evolution of Arctic snow cover through time-series of monthly basin average snow depths for the 2003-2018 period.

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Estimating Time-Variable Basal Melt Rates of Antarctic Ice Shelves: Progress and Challenges

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Current Antarctic ice-sheet mass loss is primarily driven by a decrease in buttressing as ice shelves lose mass by excess melting due to intrusions of warm ocean water. Ice-shelf melt rates can be determined using height changes derived from satellite and airborne altimetry, with auxiliary data from regional atmospheric and firn modelling, and ice velocities. Current estimates of continent-wide basal melt rates from altimetry are limited to averages for the period 2003-2009, during which time-averaged ice-shelf height change rate was measured by the laser altimeter onboard NASA's ICESat. However, this record provides no information on temporal variability and, with the exception of the large southern ice shelves (Filchner-Ronne and Ross), only poorly resolves spatial structure of trends due to orbit and sampling characteristics (including data loss when clouds are present). At the lower latitudes where most variability in ice-shelf height has been observed, track spacing is very coarse. To improve understanding of melt rate variability, e have constructed a time series of ice-shelf height change across Antarctica using the ERS-1, ERS-2, Envisat, and CryoSat-2 radar altimeters spanning 1994-2017, which we are using to investigate ocean interactions with the ice shelves. However, deriving a time series of basal melting from the height record relies on improvements in (i) firn modelling and (ii) our understanding of Ku-band radar interaction with the near-surface firn layer. For (i), we compare height changes over regions of grounded ice where we don't expect a significant ice dynamic contribution with height changes estimated from firn modelling. For (ii), we compare laser altimetry from ICESat and Operation IceBridge with radar altimetry from Envisat and CryoSat-2, respectively. The laser reflects from the top surface of the snow or firn and thus can be used to distinguish between a vertically moving internal Ku-band reflector and height changes at the true surface. In regions where the radar-derived time series is consistent with changes at the true surface, we derive a time series of basal melt rates spanning 1994-2017. Such long term observations of melt rates are difficult to make using in-situ techniques, and can provide crucial constraints to ice-shelf/ocean models.

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Monitoring Measurement Performance Of The CryoSat SIRAL Level 2 Data Products

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UCL-MSSL has a long involvement in the CryoSat mission, from the proposal stage, through the development of the data processing facility and continuing today in an expert support role to ESA providing an operational monitoring QA service for data products.

We present the results of monitoring the SIRAL Level 2 data products from the beginning of the mission in 2010 up to the present day. We describe the monitoring processes applied and the performance metrics that can be observed. We show mission performance trends, features and anomalies and discuss what factors each can be attributed to. An analysis is made of each of the various contributions (improved retrackers, slope models etc.) to successive processor baseline upgrades.

Finally we provide explanations of the differences introduced by the latest 'Baseline-D' processor.

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Radar vs LiDAR: Where Are Their Reflective Surfaces in Vegetation and Ice/Snow?

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The recent release of a global 12-m spatial resolution Digital Elevation Model, the TanDEM-X DEM, has provided elevation information for any continent and any landcover with an approximate vertical accuracy of 1-2 m. Recent accuracy assessments of this radar derived DEM (e.g. Rizzoli et al, 2017) have proven that this accuracy is achieved for approximately 90% of the Earth' land surface. However, the accuracy of this radar product was defined through comparison with global GNSS observations and ICESat satellite laser altimetry data. Both datasets provide pointwise locations which are mostly located in non-vegetated terrain. The objective of this project is to analyse the difference of the TanDEM-X radar DEM over diverse landcover types in Switzerland by comparing it with ICEsat laser altimetry, the airborne LiDAR derived 2-meter swissalti3D Digital Terrain Model, a 2-meter vegetation model, and snow/ice models derived from photogrammetry and LiDAR. The objective is to identify the reflective surfaces of radar and LiDAR signals used to derive an elevation model. Results demonstrate that radar shows variable penetration into the canopy of vegetated areas, and variable penetration into the snow/ice surface. We have derived functional relationships between radar penetration depth and tree height, tree type, canopy closure, and ice/snow cover. The results allow for an improved assessment of the uncertainty of altimetry derived DEMs and ice/snow surface change estimates used to derive ice mass balance and its contribution to sea level change.

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Results from the ESA Arctic+ Snow Project

Tsamados M.[1], Buzzard S.[1], Lawrence I.[1], Stroeve J.[1], Haas C.[2,3], Hendricks S., Rinne E.[5], Armitage T.[4], Bulczak A.[6], Ridout A.[1]
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We will present an overview of the results of the Arcrtic+ snow project. Two new snow on sea ice products will be described. Snow on sea ice represents both a major source of uncertainty in sea ice concentration and thickness retrievals from satellite data, and a poorly resolved quantity of climatic importance. The overarching objective of this project was to address these issues and to produce a state of the art snow on sea ice thickness and density product. To achieve this goal we used data from the most advanced and recent EO missions in combination with model results from reanalysis.

We utilize a comprehensive array of airborne and in-situ snow measurements to develop and validate two independent approaches to snow thickness retrieval on Arctic sea ice. In the Dual-altimeter Snow Thickness (DuST) product, we utilize data from multiple contemporary satellite altimeters to derive information about the snow layer. In the SNOw on Drifting Sea Ice (SnoDSI) product we utilize satellite-derived sea ice drift and precipitation from atmospheric reanalysis to build a package that accumulates, redistributes and melts snow on individually tracked ice parcels at daily resolution. Because of the impact of the snow thickness and density estimates for sea ice thickness retrievals this project feed in with the Arctic+ Theme 2: Sea Ice Mass project and Arctic+ Theme 5: Inverse Modelling.

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Multi-Decadal Arctic Sea Ice Roughness.

Tsamados M.[1], Nolin A.[2], Petty A.[3], Stroeve J.[1], Landy J.[4], Haas C.[5], Ardhuin F.[6], Muller P.[7], Kharbouche S.[7]
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The transformation of Arctic sea ice from mainly perennial, multi-year ice to a seasonal, first-year ice is believed to have been accompanied by a reduction of the roughness of the ice cover surface.

This smoothening effect has been shown to (i) modify the momentum and heat transfer between the atmosphere and ocean, (ii) to alter the ice thickness distribution which in turn controls the snow and melt pond repartition over the ice cover, and (iii) to bias airborne and satellite remote sensing measurements that depend on the scattering and reflective characteristics over the sea ice surface topography.

We will review existing and novel remote sensing methodologies proposed to estimate sea ice roughness, ranging from airborne LIDAR measurement (ie Operation IceBridge), to backscatter coefficients from scatterometers (ASCAT, QUICKSCAT), to multi angle maging spectroradiometer (MISR), and to laser (Icesat) and radar altimeters (Envisat, Cryosat, Altika, Sentinel-3).

We will show that by comparing and cross-calibrating these different products we can offer a consistent multi-mission, multi-decadal view of the declining sea ice roughness. Implications for sea ice physics, climate and remote sensing will also be discussed.

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25 Year Time Series of Multiple-Satellite Ice Sheet Changes: the ESA Climate Change Initiative

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Understanding the long-term changes in the ice sheets of Greenland and Antarctica has global climate significance, especially on long term global sea level rise predictions. Having validated satellite data on current and recent past changes of the ice sheets are crucial for validating climate and earth system models, and give good opportunities for space geodesy to play an important role for society.

Under the ESA Climate Change Initiative two projects on Greenland and Antarctica ice sheet changes are making past and present space measurements of the ice sheets available for use by scientists, stakeholders and the general public. The data are part of a large set of ECV's (Essential Climate Variables) made available by the ESA Climate Initiative, as a contribution to the global Climate Observing System.

The ECV data produced include detailed elevation change data from radar altimetry ice flow velocities from synthetic aperture radar missions, mass changes from GRACE, as well as data of glacier and ice shelf grounding lines and (for Greenland) glacier calving front locations from radar and optical data.

In the poster we highlight current CCI results on changes in Greenland, with special focus on 25 year elevation changes from ERS-1, ERS-2, Envisat and CryoSat, as well as the Greenland-wide velocity mapping, and the GRACE mass change results.

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Assessing Stability and Precision of Sea-Ice Thickness Retrievals from Satellite Altimetry by a Cross-over Analysis

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A climate data record of sea ice thickness derived from satellite radar altimetry that has been developed for both hemispheres, based on the 15-year (2002-2017) monthly retrievals from Envisat and CryoSat-2 and calibrated in the 2010-2012 overlap period. In addition, a sea-ice thickness retrieval from ICESat laser altimetry measurements is available from 2003-2008. In order to assess the stability and precision of these three different ice thickness products, we present a novel approach using cross-over analysis over sea ice. As an advantage over other performance indicators, this method is independent of validation data. In order to minimize the impact of random noise of single measurements, we calculate differences between ice thickness retrievals derived from two crossing satellite orbits within a 12.5 km radius around the cross-over. Moreover, we only consider cross-overs within a 24 h window to minimize the impact of sea ice drift. This study shall be a step forward to further constrain the precision of recent altimeter missions used to derive sea ice thickness retrievals.

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Sensitivity Analysis of Different Processing Approaches on Ice-Volume Change Estimates of Greenland and Antarctica

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Recent contribution of ice sheets to sea level change is of relevance for the society and a challenge but at the same time one of the major tasks of altimetry.

Within the past 25 years a set of different altimetric sensors observed the polar latitudes leading to a continuous time series of surface elevation change.

For the assessment of the contribution of ice sheets to sea level change a robust and consistent processing, as well as the estimation of uncertainties is important. However, due to different sensor characteristics, geographical coverage, orbit orientation, acquisition modes and agency data products this task is challenging. For this purpose we process altimeter data from the past 25 years using different approaches to analyse the sensitivity of volumes change estimates on a set of processing parameters, like re-tracker, backscatter and topographic slope correction. We will present time series of different periods and sensors of volume change estimates for the Greenlandic and Antarctic ice sheet and will focus on the observed largest differences.

Finally we will try to find a best case processing scenario for all sensors to be merged to a reliable long term time series.

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Snow Depth on Sea Ice for 2013-2017 Arctic Winters from CryoSat-2 and SARAL Inter-Comparison

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Snow depth at the top of sea ice is a key parameter of the climate change due to its isolation and albedo properties, which condition the sea ice growth and melt, the heat absorption and the primary production under the ice. Moreover, for several reasons that will be described in this presentation, the lack of knowledge about the snow depth can impact sea ice thickness retrieval using altimetry with an error that can reach up to 100% in the worst cases.

Nevertheless, there exists currently no reliable snow depth product at pan-arctic scale: indeed, the Warren (1999) climatology, frequently used to convert freeboard to sea ice thickness, has been built with data obtained decades ago, before the first impacts of the climate changes, and the meteorological re-analyses fail to faithfully reproduce snow falls in the Arctic.

A study published in [Guerreiro et al., 2016] has shown that the difference of the scattering properties of the Ku-band and the Ka-band can provide a good proxy of the snow depth using an adapted processing chain, Alti Snow Depth (ASD). As a first demonstrator, the ASD chain has been applied on the Ka measurements, issued from Saral/AltiKa, a French-Indian satellite, and on the corresponding Ku measurements, issued from the European satellite altimeter CryoSat-2/SIRAL. These two altimeters are based on different technics and the ratio between the surface areas illuminated by each radar is about one order of magnitude. In order to make the AltiKa LRM measurements comparable to the CryoSat-2 SAR measurements, these last ones have been pre-processed by the CNES in a degraded PLRM mode. The evaluation of the ASD product in regards with the Operation Ice Bridge snow radar data shows a good correlation (R=0.67), much better than all previous solutions. Nevertheless the results were limited to two winter campaigns.

This talk will present the results for the period extended to the four CryoSat-2/Saral common years (2013-2017). Their performance in regards with several in-situ datasets, including some CryoVex/Karen 2017 transects, will be analyzed.

Acknowledgement: this work has been supported by the CryoSeaNICE ESA project.

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Changes in Antarctic Ice Sheet Surface Elevation from a Quarter-century of Combined Radar and Laser Altimetry

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Satellite altimetry provides the longest continuous record of elevation change for assessing the mass balance of the Antarctic Ice Sheet, providing a unique opportunity to observe the ice sheet's response to changes in atmosphere and ocean over the last few decades. The accuracy of altimetry-measured elevation change, from which this mass balance is derived, is of vital importance for quantifying Antarctica's contribution to sea-level rise, and for understanding the physical processes governing changes of the ice sheet. Studies have shown that the rate of Antarctica's mass loss has accelerated over the last decade, largely a result of accelerated ice flow from the Amundsen Sea sector of West Antarctica. Not all areas of the ice sheet are thinning however. Increases in precipitation have resulted in rapid thickening over parts of East Antarctica, especially in Dronning Maud Land. A key question is how these relatively recent changes contrast against the observed longer-term trend and variability. Observations from overlapping satellite altimeter mission over the last three decades can help to answer this question. Here, we have developed a novel framework for cross-calibrating and synthesizing multi-mission altimetry records, with a further emphasis on generating state-of-the-art corrections for issues affecting the altimeter measurement (such as surface slope and variations in surface scattering) in order to increase the reliability and accuracy of the full altimetry record. The framework allows us to construct consistent time series at fine spatial and temporal scales for the majority of the ice sheet, with a corresponding assessment of the overall uncertainty of the solutions. We present results detailing the complex long-term pattern of elevation change, observed by the altimeters, and discuss the current improvement and limitations of the altimeter record. This effort will allow us to improve upon existing records of the long-term evolution of the Antarctic Ice Sheet, providing an invaluable dataset for advancing ice sheet modeling efforts and for disentangling the causal mechanisms responsible for ice sheet mass change.

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Sea Ice Freeboard from ICESat-2 Multi-Beam Altimetry

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ICESat-2 is a multi-beam photon-counting lidar on the ICESat-2 observatory (launch: September 2018). This mission will provide observations to quantify changes in the sea ice covers of the Arctic and Southern Oceans. Here, we briefly describe the phenomenology of photon distributions in the sea ice returns, our approach for finding the heights of the ice and water surfaces, and the achievable height precision. Retrieved surface heights over relatively flat leads in the ice cover suggest that precisions of several centimeters can be attained. Comparisons of nearly coincident elevation profiles from MABEL (Multiple Altimeter Beam Experimental Lidar – an airborne instrument) with those acquired by an analog lidar show good agreement. Discrimination of ice and open water, a crucial step in the determination of sea ice freeboard and the estimation of ice thickness, is facilitated by contrasts in the observed signal/background photon statistics.

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Towards an Operational Snow Depth and Density Product for use in Radar Altimetry

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Several radar altimetry missions have been flown since the early 1990s, providing for the first time the ability to estimate sea ice thickness on a larger scale than achieved by submarines and aircraft. Radar altimeters from ERS-1, ERS-2, Envisat and CryoSat-2 now provide a continuous data set of sea ice freeboard spanning 2 decades, however, different radar configurations have made blending these data challenging. Another complication is that snow depth and snow density are required for the conversion from radar freeboard to sea ice thickness. Usually, climatological values of snow depth and density are used, which removes inter-annual variability of snow accumulation. Since snow accumulation can vary substantially from year to year, sea ice thickness will be biased as well.

The aim of this work is to present a novel snow depth and snow density data product that can be used to derive sea ice thickness from multiple platforms over the entire satellite data record. The approach is based on a physical snow evolution model to account for snow redistribution, compaction, melt and metamorphosis. The impact of this snow depth and density product is tested on retrieved sea ice thickness in the CryoSat-2 processing chain.

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Use of Satellite Altimeter Data for Comparison and Calibration of Century Based Wind and Wave Climate Data Record

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Reliable wind and wave data affecting a coastal region is very essential for almost all coastal and marine activities. Especially for the design of the coastal structures, not only reliable but also long-term data is necessary. Satellites that are equipped with instruments capable of observing marine surface wind and ocean waves like Radar Altimeter (RA), Synthetic Aperture Radar (SAR) and Scatterometer provide remotely sensed observations data. Such data source has good global coverage and is usually very reliable. However, the time period is not enough to construct a record suitable for climate computations. Therefore numerical model estimates are commonly used because of their wide temporal and spatial coverage as well as lower cost. For example, European Centre for Medium-Range Weather Forecasts (ECMWF) has been producing wind and wave parameters for the last few decades. ECMWF has also carried out several reanalyses (e.g. ERA-Interim) to extend the climate record by several decades in the past using the same model version. All the reanalysis cover the period from 1979 to the present. ECMWF with the help of several international organizations started a new reanalysis Project (the ERA-CLIM Project). In order to produce consistent reanalyses of the climate system, reaching back in time as far as possible given the available instrumental record, ECMWF has produced the uncoupled atmospheric reanalysis ERA-20C, which covers the period January 1900 to December 2010. ERA-20C assimilates only conventional observations of surface pressure and marine wind, obtained from well-established climate data collections. Then, as a second phase, ECMWF has completed the production of a new global 20th-century reanalysis which aims to reconstruct the past weather and climate of the Earth system including the atmosphere, ocean, land, waves and sea ice. This coupled climate reanalysis, called CERA-20C, is part of the EU-funded ERA-CLIM2 project. Both data are available at 3-hour time increments. Literature study shows that new century long data have started to become an attractive source for the researchers dealing with climate studies.

In this study, main purpose is to derive the wind and wave climate along the Turkish coasts based on a century long data of ERA-20C and CERA-20C. For this purpose, first of all, wind speed (u10) and significant wave height (SWH) data of ERA-20C and CERA-20C are compared by using ENVISAT RA measurements over the whole Black Sea for 2007-2008 as a pilot study. Comparison results show that both data give similar results but CERA-20C seems to be better from the significant wave height side of view. Then CERA-20C data are calibrated and validated by using satellite RA data set. For the calibration, ERS-1 (1991-1996), ERS-2 (1995-2011) and ENVISAT (2002-2012) RA data are inter-calibrated to get consistent satellite data sets. In-situ measurements and recent reanalysis data ERA5 of ECMWF are used for the inter-calibration. Wave period is also predicted from RA backscatter coefficients (Ku and C bands), significant wave height and wind speed by using Neural Network Method and used for the calibration of CERA-20C wave period

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Corsica: A 20-yr Multi-Mission Absolute Altimeter Calibration Site

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Initially developed for monitoring the performance of TOPEX/Poseidon and follow-on Jason legacy satellite altimeters, the Corsica geodetic facilities that are located both at Senetosa Cape and near Ajaccio have been developed to calibrate successive satellite altimeters in an absolute sense. Since 1998, the successful calibration process used to calibrate most of the oceanographic satellite altimeter missions has been regularly updated in terms of in situ instruments, geodetic measurements and methodologies. The calibration process is based on both indirect and direct calibration/validation approaches. The indirect approach utilizes a coastal tide gauge and, as a consequence, the altimeter derived Sea Surface Height (SSH) needs to be corrected for the geoid slope. Other factors including ocean dynamics and tidal differences impact the comparisons with independent coastal in situ measurements but are negligible in such areas and within the short distance in our study (less than 20 km). The direct approach utilizes a novel GPS-based system deployed offshore under the satellite ground track that permits a direct comparison with the altimeter derived SSH.

In this study, we present an assessment of the long-term stability of the in situ instruments in terms of sea level monitoring that include a careful monitoring of the geodetic datum. Based on this 20-yr series of sea level measurements, we present a review of the derived absolute SSH biases for the following altimetric missions based on the most recent reprocessing of their data: TOPEX/Poseidon and Jason 1,2,3, Envisat and ERS, CryoSat 2, SARAL/AltiKa and Sentinel 3A.

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Updates to the Geosat 30th Anniversary Data Set

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The U.S. Navy's Geosat mission yielded the first multi-year high-precision radar altimetry data set, and provides the only global sea surface height measurements from the late 1980s. NOAA has produced several versions of the Geophysical Data Records (GDRs) for the mission, with the most recent data release in 1997. This was the first set of GDRs that spanned both the Geodetic Mission (GM: March, 1985 to September, 1986) and Exact Repeat Mission (ERM: November, 1986 to December, 1989). In April, 2009 we concluded a major data archaeology effort to recover the original Sensor Data Records (SDRs) for the ERM from 9-track tapes. After the SDRs are combined with their companion Waveform Data Records (WDRs) it is possible to retrack the original radar echoes, yielding an improved level-2 data set. This had previously been done for the GM in 2004, and has now been completed for the ERM as well. This presentation describes the steps involved in assembling the full GM +ERM retracked altimetry data set. A major enhancement involves the calculation of precise orbits based on the latest gravity models, terrestrial reference frames, and Doppler station coordinates, with improved Vienna Mapping Function atmospheric refractions. The best possible geophysical corrections are provided, along with the retracked sea surface heights, including GOT4.10 and FES2014 tide models, ERA-Interim tropospheric corrections, NIC09 climatological ionospheric corrections, and a new sea state bias model. Updates since the 2015 OSTST include a new, robust method to compress the range [and other high-rate data] from 10-Hz to 1-Hz values. The waveform information is now preserved in a 2D array, so that the resulting SGDRs are similar in format to those from the Jason missions. In cases of missing WDR waveforms, the original SDR values have been preserved for posterity's sake. This 30th Anniversary release will be openly available to the community via RADS-4. Ultimately our hope is to extend the altimetric sea level climate data record back to 1985, with the inclusion of these retracked Geosat measurements.

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Saral/Altika Altimetry Data Processing for Determination of the Mean Sea Surface over the Western Mediterranean Sea

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Altimeter is an instrument used to accurately measure the sea surface height. The objectives of altimeter mission are to realize precise, repetitive global measurements of sea surface height, significant wave height and wind speed for developing operational oceanography, understanding of climate and developing forecasting capabilities

Since 2013, SARAL marks a change in the instrumental characteristics compared to previous missions, because it transmits in Ka band (36.75 Ghz) instead of the Ku (13.6 Ghz) and S (3.2 Ghz) bands which implies an interaction with the different surface that needs to be understood.

Indeed, the wavelength of the band k which is of the order of 8 mm, allows a better description of the small facets slopes of the sea surface on one hand, on the other hand, a most precise measurement of the backscattering coefficient.

The present work is based on the determination of the mean sea surface (MSS) above a reference ellipsoid over the Western Mediterranean Sea by processing (01) one year of Saral/Altika Geophysical Data Records (10 cycles). Environmental corrections (Ionospheric, Wet Tropospheric and Dry Tropospheric corrections) then have to be made as the radar pulse is affected by travelling through the atmosphere, and geophysical corrections (Sea State Bias, Tides) have to be made also.

The comparison of the obtained mean sea surface with the mean ocean surface MSS_CNES_CLS2015 provided by AVISO gives a difference of -0.029m with a standard deviation of 0.067cm.

This work allowed us to study the Altika altimeter performance, particularly the contribution of the Ka band to the quality of obtained results.

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Estimating Trend Uncertainties of Global Mean Sea level Evolution over the 25-Year Altimetry Era

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Satellite altimetry missions now provide a more than 25 years record of continuous measurements of sea level along the reference ground track of TOPEX/Poseidon. These measurements are used by different groups to build the mean sea level rise record, which is an essential climate change indicator. Estimating a realistic uncertainty on the sea level rise rate deduced from satellite is of crucial importance for climate studies such as sea level budget closure.

Ablain et al., 2015 estimated the GMSL trend uncertainty 0.5 mm/yr (90% confidence interval) by a careful study of the differences between altimeter standards. In this study we update this study over the 25-year altimetry era, tuning the modelling of altimetry errors. We use a generalized least squares approach, based on the a priori knowledge of the error variance-covariance matrix. Three types of errors that can affect altimetry are modeled (drifts, biases, noise) and combined to derive realistic confidence intervals on local sea level trend estimates. The approach is extended to estimates the GMSL trend uncertainties over the 25-year period, but also for any altimeter periods between 1993 and 2017 years. Furthermore, a confidence envelop of the GMSL time series is inferred from the error variance-covariance matrix.

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Calibration and Intercalibration of the ERS-1/ERS-2/Envisat Microwave Radiometer Time Series: ESA's MWR EMiR Project

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The Microwave Radiometer (MWR) flown on Envisat, ERS-1 and ERS-2 provides a nearly uninterrupted time series of microwave observations over a period of almost 21 years between 1991 and 2012. This dataset is complementary to other microwave datasets, such as e.g. the Special Sensor Microwave Imager (SSM/I) datasets. Despite its nadir-only coverage it provides an opportunity to independently provide estimates on total column water vapor (TCWV) and cloud liquid water path (LWP).

Here we report on our efforts towards a fully inter-calibrated and validated physical retrieval of TCWV and LWP for MWR. We will address issues related to satellite inter-calibration, homogeneity of the derived time series of brightness temperatures, observation-simulation biases, and provide results of fully physical optimal estimation retrievals of TCWV. An outlook on planned activities will be given and the importance of the results in light of the continued availability of MWR observations through the Sentinel-3 mission will be discussed.

We finally analyze the impact of the EMiR TCWV on wet tropospheric correction (WTC) of ocean altimetry observations and subsequently identify a number of potential improvements

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Developing Long-Term Consistent Altimeter Datasets for the Sentinel Era

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The launch of Sentinel-3B in April 2018 marks a major step in the plans for global monitoring of the Earth's surface with delay-Doppler altimetry. This mode of processing (also known as 'SAR altimetry') offers finer spatial resolution, more independent looks, lower noise levels and greater resilience to unwanted echoes in the coastal zone. However, there are many challenges in validating expected performances and removing any biases between instruments. The Sentinel-3 Mission Performance Centre (S3MPC) is charged with assessing the data quality coming from both Sentinel-3A and Sentinel-3B.

This talk will focus on results from the first few months of the tandem phase, which permits a very precise intercalibration of the two sensors, with comparisons of performance over ocean and land, and evaluation for range, wave height and wind speed. Achieving a high consistency between the two missions is critical to their use in near real-time monitoring of various oceanic parameters. Initial assessment of relative performance in the cryosphere will focus on the Lake Vostok and SPIRIT regions that offer the contrasting environments of gentle and steep topography. We will also compare the output of the microwave radiometers that provide essential atmospheric corrections. As this presentation will be early in the Sentinel-3B lifetime, it may illustrate some of the challenges i achieving the desired level of consistency. These comparisons will be indicative of future work to establish a uniform homogeneous SAR altimetry dataset later also spanning Sentinel-3C and 3D, but also, through the comparison of LRM and SAR cycles will provide a clear link to heritage altimetry datasets.

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CryoSat Precise Orbit and Long Term Ocean Data Analysis and Validation

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ESA's Earth Explorer mission CryoSat is dedicated to precise measurement of the changes in the thickness of marine ice floating on the polar oceans and variations in the thickness of the ice sheets that overlie Greenland and Antarctica. The CryoSat-2 spacecraft was launched on 8 April 2010.

With the effects of a fast-changing climate becoming apparent, particularly in the Polar Regions, it is increasingly important to understand exactly how Earth's ice fields are responding. Diminishing ice cover is frequently cited as an early casualty of global warming and since ice plays an important role regulating climate and sea level, the consequences of change are far-reaching.

To understand fully how climate change is affecting these remote but sensitive regions, there remains an urgent need to determine exactly how the thickness of the ice, both on land and floating in the sea, is changing. By addressing this challenge, the data delivered by the CryoSat mission is completing the picture and will lead to a better understanding of the ice role in the Earth system.

In order to achieve this, the quality of the CryoSat orbit and the altimeter data has to meet the highest performance, and this not only over the ice caps and sea-ice surface but over the oceans as well.

This paper describes the results of the author's activities to validate CryoSat Precise Orbit and SIRAL Ocean altimeter products, referred to as the Geophysical Ocean product (GOP) generated by the CryoSat Ocean Processor. They consist of the determination of precise orbit solutions and assessment of the Cryosat mission precise orbit products, and of the long-term monitoring, validation, and cross-calibration of the GOP data with the support of the Radar Altimetry Database System (RADS), external measurements and numerical models. The goal is to evaluate the stability of the measurement system and the identification and explanation of possible biases and bias drifts.

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CryoSat-2 Range, Datation and Interferometer Calibration with Transponders

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Transponders are commonly used to calibrate absolute range from conventional altimeter waveforms because of their characteristic point target radar reflection. The waveforms corresponding to the transponder distinguish themselves from the other waveforms resulting from natural targets, in power and shape.

ESA deployed a transponder available for the CryoSat mission (a refurbished ESA transponder developed for the ERS-1 altimeter calibration). It is located at the KSAT Svalbard station: SvalSAT. The transponder is used to calibrate SIRAL's range, datation, and interferometric phase (or angle of arrival) to meet the mission requirements. Another transponder, deployed in 2015 in Crete for the Sentinel 3 calibration, has been included in the analysis.

In these calibrations, 3 different types of data have been used: the raw Full Bit Rate data, the stack beams before they are multi-looked (stack data) in the Level 1b processor, and the Level 1b data itself.

Ideally, the comparison between the theoretical values provided by the well-known target, and the measurement by the instrument to be calibrated provides us with the error that the instrument is introducing when performing its measurement. When this error can be assumed to be constant regardless the conditions, it will provide the bias of the instrument.

If the measurements can be repeated after a certain period of time, it can also provide an indication of the instrument drift. This paper presents the range, datation and angle-of-arrival errors from the transponder data of seven years of Baseline C data to derive potential biases and drifts

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From Conventional to High Resolution Delay Doppler Altimetry: a Review of the Altimeters Performances over Ocean

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The ocean topography observability at global scales started in the nineties with the launch of the altimetry satellites ERS1, TOPEX/Poseidon and ERS2. In addition to the rapid and global coverage provided by the spatial altimetry technic, the onboard altimeters allowed to measure the Sea Surface Height with a precision of 4 cm. It was the beginning of a revolution in the understanding of oceanic global circulation. Until 2010, other altimetry missions (Jason-1, Envisat, Jason-2) were launched to improve the spatial coverage and maintain the historical ground track used to monitor the Global Mean Sea Level.

The launch of Cryosat-2 in 2010 and SARAL/AltiKa in 2013 marked the beginning of a new altimeters generation and the rupture between conventional Ku-band altimetry and new technologies that are expected to improve the measurement accuracy.

The Cryosat-2 altimeter SIRAL is based on a different principle proposed by Raney (1998): The Synthetic Aperture Radar mode (SARM) also referred to as Delay Doppler Mode. The altimetry community exploited this opportunity to process and analyse these new measurements. SARM data sets analyses presented in 2012, 2013 during the OSTST meetings, demonstrated the potential of this technique to retrieve finest ocean scale signals. Following the recommendation from the scientific community and the Copernicus Marine Service, this mode is implemented on Sentinel-3A (launched more recently, in 2016) with, for the first time, a global coverage.

This paper aims at describing and quantifying the evolution of the altimeter performances over ocean and the transition between classical Ku-band LRM datasets and SARM technologies. It will focus on the assessment of several SARM data sets, derived from different processing to illustrate the progresses made to ensure the seamless transition as possible

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Tropospheric Corrections for Satellite Altimetry: Main Achievements and Perspectives

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The path delay in the radar signal as it propagates through the troposphere in its way towards and after its backscatter from the Earth's surface is the largest range correction in satellite altimetry. The dry component (dry path delay, DTC), due to the neutral gases in the atmosphere, has an absolute mean value of 2.3 m and a small space-time variability, not exceeding 10 cm. On the contrary, the component due to the water vapour and liquid water (wet path delay, WPD) has a smaller value, from 0 to 50 cm, but a large (close to 100%) space-time variability. This paper aims at reviewing the main progress achieved during the last decade in the modelling of the tropospheric corrections of satellite altimeter observations.

As the DPD can be determined within a few millimetres from surface pressure values, the progress in its modelling is mainly associated with the improvement in numerical weather models, the European Centre from Medium Weather Forecasts (ECMWF) being of particular relevance.

Due to its large variability, both in space and time, the WPD is best retrieved from collocated measurements from microwave radiometers (MWR) embarked on altimeter missions. Because these instruments have a footprint larger than the altimeter footprint (10-40 km, depending on frequency) and the WPD retrieval algorithms assume a constant ocean emissivity, the MWR observations become invalid over non-ocean surfaces, in particular in coastal and polar zones. In the last decade, intensive research has been made at tackling the problem of improving the WPD retrieval in these regions, also leading to the improvement over open-ocean. Some methods focused on the direct removal of the effect from non-ocean surfaces on the Brightness (TB) Temperatures, while others were dedicated to the WPD retrieval using data combination methods, whereby the invalid WPD MWR values are replaced by new estimates using available WPD observations and model values. Thanks to these developments, accurate and continuous tropospheric corrections are now available for most altimeter missions, contributing to the extension of altimeter studies to coastal zones and continental waters.

Regarding coastal and inland water zones, some of the present issues are related with the height dependence of the tropospheric corrections, requiring proper modelling of this effect. Moreover, in view of the full exploitation of improved measurements from new instruments, measurement modes and retracking algorithms, the need for high rate tropospheric corrections become apparent.

This paper presents an overview of the most relevant developments in the tropospheric corrections pursued by the altimeter community and discusses the main challenges, in particular those related with the new instruments to be deployed in future missions such as Sentinel-6 and SWOT.

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Evaluation of Delay-Doppler SAR Processing Algorithms Over Open Ocean

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During the last decade the radar altimetry has entered in its golden age as demonstrated by the different number of missions (Jason-3, CryoSat-2, SARAL/Altika, Sentinel-3a) currently operating and continuity missions planned for the near future (Sentinel-3b, Sentinel-6). The relatively new operational SAR mode in CryoSat-2 and Sentinel-3 missions, opens a new paradigm in the capabilities offered by satellite radar altimeter missions.

The core of this presentation explores comparatively different processing options in an isardSAT in-house Delay-Doppler chain, exploiting the high-resolution data acquired by CryoSat-2 in the SAR mode over open ocean areas. The data set considered in the analysis has been provided under the framework of SCOOP (SAR Altimetry Coastal and Open Ocean Performance) project funded under the ESA SEOM (Scientific Exploitation of Operational Missions) Programme Element.

Different state-of-the-art processing baselines have been considered: the nominal CryoSat-2 and Sentinel-3 baselines are comparatively evaluated. Additional settings on the processing baseline are assessed as well. Finally the promising ACDC (amplitude compensation and dilation compensation) algorithm is integrated and implemented at stack level.

ACDC was originally proposed by Chris Ray and isardSAT team within the Sentinel-6 Ground Prototype Processor (GPP) project. The basic idea is to perform a two-step compensation once the stacking has been performed and right after geometry corrections application: 1) along-track amplitude compensation to equalise the Doppler-dependent weighting induced by the acquisition geometry in combination with both antenna and surface radiation patterns; and 2) across-track dilation compensation to correct for the waveform widening when moving away from the central beam. In this way, a better alignment of the waveforms within the stack is obtained by focusing the spread along-track energy into a single range bin, such that an improved speckle reduction and signal-to-noise ratio (SNR) are expected. This results in a simpler and more computationally efficient analytical retracker over ACDC L1B waveforms when compared to the conventional SAR analytical retracker on L1B waveforms.

The performance of the different processing baselines is analysed in terms of the precision of retrieved geophysical parameters. A dedicated in-house L2 processor, integrating the first fully analytical SAR ocean model (Ray et al 2015), has been exploited. This analytical retracker was adapted side by side with the L1B processing in order to create an L1B waveform modelling which was as accurate as possible. The objective is to gain insights into the most suitable processing options in the L1B+L2 chains, so an improvement in terms of noise estimation of different geophysical parameters can be achieved.

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The Permanent Facility for Satellite Altimetry Calibration in Gavdos/Crete, Greece: Fifteen years of Cal/Val Service.

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This work describes the gradual development of the Gavdos/Crete Cal/Val permanent facility as of 2001 in terms of infrastructure, instrumentation and the sea-surface as well as transponder calibrations along ascending and descending orbits of satellite altimeters. The difficulties encountered during this period are described, along with measures taken to overcome them.

Absolute calibration results are given for Jason-1, Jason-2 and Jason-3 along their ascending Pass No. 109 together with the descending Pass No.18 for 2004-2017. Sea-surface Cal/Val results for Jason-3 are compared against transponder calibrations carried out along the same orbit at the CDN1 Cal/Val site on the mainland of Crete. Relative calibrations are also given between Jason-3 and Sentinel-3A & 3B simultaneously with sea-surface and transponder techniques. Other Cal/Val results for past satellites such as SARAL/AltiKa and the Chinese HY-2 will also be reported.

Guidelines for keeping an accurate, reliable, objective, homogeneous and continuous monitoring of oceans, inland waters as well as Polar Regions with altimetry will also be given. Transparent protocols and best practices for establishing new Cal/Val sites according to the standards of Fiducial Reference Measurement for altimetry will be presented

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International Standardization for Satellite Altimetry Calibration: Lessons from the Past and Roadmap to the Future.

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Satellite altimetry today provides exceptional means for absolute and undisputable monitoring of changes in sea level and inland waters (rivers and lakes), over regional to global scales, with accuracies of [mm/yr] and with respect to the center of mass of the Earth. Altimetry also measures wind speed on sea surface, sea state, determines ocean circulation, bathymetry, but also monitors melting rates of ice sheets in Arctic, Antarctica, and the Himalayas and observes the amounts of the sea ice and freeboard; All these with an accuracy less than 1cm from an attitude of 800-1300 km above the earth's surface.

To continue doing that, altimetry system's responses have to be continuously monitored and controlled for their quality, biases, errors, drifts, etc. Relations among different missions have to be established on a common and reliable earth-center reference system, maintained for a long period of time (at least 20 years).

At this stage, it is high time to (1) Build upon commonly adopted procedures, protocols and uncertainty for Cal/Val, (2) Provide control and checks for monitoring altimeter degradation as fast as possible, (3) Connect one altimetry mission with another, seamlessly and smoothly, (4) Adopt a stable framework for international and interdisciplinary cooperation, (5) Allow data integration between different scientific fields and disciplines, (6) Set standards for measurements and results between various Cal/Val facilities, (7) Ensure Cal/Val procedures, results are well documented and traceable to SI units, (8) Provide transparent protocols and best practices for establishing new Cal/Val sites and finally, dissipate responsibility to end user to decide the extent of fit for his requirements.

This presentation generates a summary roadmap to be used by all satellite altimetry Cal/Val community to (1) support accuracy in scientific and monitoring data we produce and evaluate, (2) to provide accurate information presented to the Public for understanding effects of sea level rise to their lives, and finally (3) to help make the right decisions, and put into action the right Policies for climate change. Ways to express uncertainty will be given to meet the standard of Fiducial Reference Measurements but also provide SI-traceable (Système International d'Unités) calibration results.

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The Sentinel-3 SRAL Instrumental Calibration Monitoring.

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It is well known the crucial importance of the altimeter instrumental calibration in the production of reliable and accurate L2 geophysical retrievals, such as sea surface height, significant wave height, or wind speed over the oceans.

isardSAT, as ESA Expert Support Laboratory within the Sentinel-3A/B Mission Performance Centre team, is responsible of monitoring the calibration parameters during the Sentinel-3A/B SRAL altimeter mission. Here we present the monitoring results of updated SRAL calibration data, acquired during the Commissioning and Routine Phases of the Sentinel-3A mission and Commissioning Phase of the Sentinel-3A mission.

The SRAL altimeter permits to operate in two modes, LRM (low resolution) and SAR (high resolution) in two frequency bands, Ku and C. For the 4 combinations, CAL-1, CAL-2 and Autocal calibration modes are monitored and analysed from L1b data. Also the on-board thermal variations are monitored from L0 data. The USO frequency trend check is also shown. Finally, the on-board tracker performance is studied from L2 data.

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Monitoring Long Term Variations of Arctic Sea Ice Thickness Using Several Satellite Altimetry Missions

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Arctic sea ice volume is one of the most visible indicators of climate change and is an integrated measure of arctic sea ice energy and freshwater budgets. Monitoring sea ice volume variations on long time scales is therefore crucial to understand climate processes related to sea ice changes. While sea ice extent has been monitored over 40 years using passive microwave imagery, the current observations of sea ice thickness based on satellite altimetry span on much shorter periods (usually less than 10 years) and do not allow estimating long term sea ice volume variations.

In this presentation we will show that ice thickness time series can be extended to more than 20 years using a combination of satellite altimetry missions (ERS-2, Envisat, CryoSat-2 and Sentinel-3), providing that inter-missions biases are calibrated and corrected.

Among all potential inter-mission biases, the most impacting one is certainly the transition from Low Resolution Mode (LRM) to Synthetic Aperture Radar (SAR) altimetry. This transition is particularly important over sea ice as the strong surface heterogeneity at basin-scale and within the radar footprint has a different signature in LRM and SAR modes.

In this presentation, we will see how the ice thickness bias between LRM and SAR missions can be calibrated and corrected. In particular, we will focus our interest on the transition between Envisat (LRM) and CryoSat-2 (SAR) missions during their common flight period (2010-2012). To demonstrate the potential of the bias correction related to the transition of altimetric mode, we will show comparisons between calibrated ice thickness estimates and in situ observations (mooring, airborne, buoys, etc.).

We will then give an overview of other sources of uncertainties occurring when combining several altimetry missions. In particular, we will discuss the impact of SAR processing by focusing on the continuity of ice thickness monitoring between CryoSat-2 and Sentinel-3.

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Sentinel-3 Range and Datation Calibration with Crete Transponder

Garcia-Mondejar A.[1], Mertikas S.[2], Galanakis D.[2], Labroue S., Bruniquel J[6], Quartly G.[7], Féménias P.[4], Mavrocordatos C.[5], García P.[1], Roca M.[1]
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Sentinel-3 is the Earth observation satellite mission designed to ensure the long-term collection and operational delivery of high-quality measurements of, among others, the sea surface topography. Post-launch calibration and validation of the satellite measurements is a prerequisite to achieve the desired level of accuracy and ensure the return on the investment. These Calibration/Validation (Cal/Val) services are provided by independent, external Cal/Val facilities that determine the error in satellite measurements, using known and controlled signal inputs on the ground. Sentinel-3 altimeter calibration site was established in West Crete, Greece. This site has been named CDN1 Cal/Val site and is located at an elevation of Transponders are commonly used to calibrate absolute range from conventional altimeter waveforms because of their

characteristic point target radar reflection (not in the case of regenerative transponders). The waveforms corresponding to the transponder distinguish themselves from the other waveforms resulting from natural targets, in power and shape.

The transponder is used to calibrate SRAL's range and datation to meet the mission requirements. For this calibration, the S3 L1A data is processed with a specialised transponder processor. Atmospheric delays are acquired directly from the calibration site providing better accuracy to the final range measurement. Ideally, the comparison between the theoretical values provided by the well-known target, and the measurement by the instrument to be calibrated provides us with the error that the instrument is introducing when performing its measurement. When this error can be assumed to be constant regardless the conditions, it will provide the bias of the instrument. If the measurements can be repeated after a certain period of time, it can also provide an indication of the instrument drift.

The range and datation results using the Crete transponder are presented in this paper. This work is been carried out within the Sentinel-3 Mission Performance Center activity S3MPC.

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Internal Tide Oceanic Tomography

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A concept of internal tide oceanic tomography (ITOT) is proposed to monitor ocean warming on a global scale. ITOT is similar to acoustic tomography, but that work waves are internal tides. ITOT detects ocean temperature changes by precisely measuring travel time changes of long-range propagating internal tides. The underlying principle is that upper ocean warming strengthens ocean stratification and thus increases the propagation speed of internal tides. This concept is inspired by recent advances in observing internal tides by satellite altimetry. In particular, a plane wave fit method can separately resolve multiple internal tidal waves and thus accurately determines the phase of each wave. Two examples are presented to demonstrate the feasibility and usefulness of ITOT. In the eastern tropical Pacific, the yearly time series of travel time changes of the M2 internal tide is closely correlated with the El Niño–Southern Oscillation index. In the North Atlantic, significant interannual variations and bidecadal trends are observed and consistent with the changes in ocean heat content measured by Argo floats. ITOT offers a long-term, cost-effective, environmentally friendly technique for monitoring global ocean warming. Future work is needed to quantify the accuracy of this technique.

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The Democratisation of Satellite Data Processing

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This presentation will start by reviewing the progress made over the last 25-years in satellite downlink bandwidth, on-ground data processing capability, and data dissemination timeliness and bandwidth to users. The likely advances that can be predicted into the future will then be shown. This progression in capabilities stands to make mission-scale reprocessing activities a simple task in terms of computation and data-storage, opening the gateway to the end-user being able to demonstrate the benefit of a new model or algorithm at these scales. To enable this to take place, thought must be given to data-dissemination methods and data formats, both for new missions and for future reprocessing activities on completed missions. An architecture can be designed that will allow the end user to plug new models and algorithms into an existing data processing pipeline and reprocess entire mission or multi-mission quantities of data, but such an architecture requires a solid foundation of data provision, formatting, and annotation techniques to be realised. We will suggest one possible architecture, that could be provided as a cloud-based service.

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Revisiting Sea Level Trends around Venice using Tide Gauge Records and Improved Satellite-based Sea Level Products from ESA CCI Project

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Sea level is the major threat to Venice and tracking its variability is crucial to safeguard the city. Even if the MOSE barrier was designed to defend effectively against storm surges, the long term implications of gradually rising sea levels has not been sufficiently investigated. The European Space Agency (ESA) Climate Change Initiative (CCI) project on “Sea Level” has produced an improved set of satellite-based sea level products (e.g., monthly mean sea levels and trends) by reprocessing altimeter data over 1993-2013. In this poster, we assess the quality of the current Sea Level CCI products in the Adriatic Sea, and in particular around the city of Venice. We aim at determining how close to the coast the actual Sea Level CCI products can be considered reliable. Sea level measurements from tide gauges are used as references of sea level trends the coast. Comparisons with the closest CCI grid points will permit to estimate the importance of vertical land movements and identify local processes that might impact on the local sea level rise. During the CCI+ phase (2018-2019) particular efforts will be dedicated to the retrieval of sea level from altimeters in the coastal zone. This work will contribute to identify problems and challenges to extend the sea level climate record to the coastal zone with quality comparable to the open ocean.

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25 years of Wet Tropospheric Correction: Long Term Stability Assessment Using Double Difference Method

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The wet tropospheric correction (WTC) is a major source of uncertainty in altimetry budget error, due to its large spatial and temporal variability. It also contributes significantly to the uncertainty in the long term mean sea level trend.

At the occasion of the 25 years of satellite radar altimetry, the long-term stability is addressed through the analysis of all the available timeseries of the microwave radiometer data in their most up-to-date reprocessing state: from TOPEX/Poseidon, Jason-1 to Jason-3 series, the ERS-1, ERS-2, Envisat, Sentinel-3A series, and AltiKa.

In order to better quantify the WTC trend, it is important to focus on the detection of potential instrumental drifts. The long-term stability of each radiometer is here assessed using the double difference method. The double difference accounts for frequency, Earth Incidence Angle, and orbital differences between platforms. To calculate the double difference, the single differences for each radiometer are first computed. The single difference is found by taking the difference between a reference statistic of the observed radiometer brightness temperatures (TBs) and a reference statistic from simulated TBs. The double difference is then the difference between the single differences of the two radiometers [1].

Single differences suffer from the discontinuities introduced by evolutions of the Numerical Weather Prediction model due to improvements in the operational version or modification of the assimilation scheme. By construction, double differences cancel out the impact of these evolutions.

Once the long-term stability of TBs is assessed, robust conclusions can be drawn on the stability of the WTC.

[1] R. A. Kroodsma, D. S. McKague, and C. S. Ruf, "Inter-calibration of microwave radiometers using the vicarious cold calibration double difference method," IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., vol. 5, no. 3, pp. 1006–1013, 2012.

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Comparison of Linear and Nonlinear Impact to Sea Level Variability Based on Satellite Data

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We are comparing the linear and nonlinear components in the equation of potential vortex conservation based on the altimeter satellite data. We apply the analysis for two regions of the World Ocean in the southern hemisphere. The first region is one of the most dynamically changing regions of the World Ocean and is located to the south of Cape Agulhas. The second area is located in the low latitudes of the Indian Ocean. We are showing that nonlinear effects predominate in the sea level of low-frequency variability in the regions. This result confirms the earlier conclusion that nearly all features isolated by the method of automatic identification in the sea level are nonlinear. Consequently, the criterion for determining the degree of nonlinearity of structures by comparing the maximum circumferential velocity of particles with the speed of feature displacement is a reliable indicator of nonlinearity.

Comparison of linear and nonlinear components of the two regions in Southern Hemisphere has shown that in low latitudes nonlinear effects differ from linear by the order of magnitude. However, these characteristics differ by two orders of magnitude for middle latitudes. We found that in the early studies based on altimetric data researches exaggerated the impact of Rossby waves for the low latitudes of Indian Oceans.

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Key words: sea level, altimetry, mesoscale eddies, Rossby waves, relative vorticity, Okubo-Weiss parameter, Southern Ocean, Indian Ocean, SLA.

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Validation of Coastal Sea Level Rates from Dedicated Coastal Altimetry Products

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Validation of coastal altimetry sea level products against in-situ tide gauge measurements is an essential part of verifying the altimetric sea level observations. The introduction of specialised retrackers, such as Adaptive Leading-Edge Sub-waveform (ALES) has improved the estimates of the altimetric sea level rates close to the coast. One way to assess this improvement is via altimetry-tide gauge comparisons, but this is complicated by the fact that the dominant sea level signals at different tide gauges may have very different length scales. Tide gauges located in regions where signals have relatively long cross-shelf length scales generally have a better agreement with altimetry observations and provide a more accurate assessment of the altimeter's performance. Here, as part of a study conducted within the framework of the ESA Sea Level Climate Change Initiative (SL_cci) Project, we identify regions of long length scales based on the high-resolution NEMO (1/12 degree) global ocean model in order to improve the validation technique for assessing the performance of coastal altimetry products from the Jason-1, Jason-2, Envisat and SARAL/Altika missions. The tide gauges are sorted into groups according to their cross-shelf decorrelation values. The performance of the coastal altimetry observations reprocessed with specialised retrackers not yet available in missions' ground segment processors is then assessed for each group of tide gauges separately. An initial assessment by grouping tide gauges in macro-regions shows that there is a very good agreement between along-track altimetry and tide gauges where the sea level variations are correlated over relative large spatial scales such as in south eastern Australia and this is maintained up to approximately 3 km from the coast.

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Lessons Learned After 10 Years of Validation of Coastal Altimetry Products in the Gulf of Cadiz and the Srait of Gibraltar (Southwestern Iberian Peninsula)

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The Gulf of Cadiz and the Strait of Gibraltar (southwestern coast of the Iberian Peninsula) have been routinely used in the last decade as test validation sites of coastal altimetry products (sea level and significant wave height). In this work, we present a summary of the main results and conclusions obtained after comparing altimetry-based sea level data against sea level from tide gauges located in the study area. The validation was performed at different spatio-temporal scales: (i) Monthly/weekly/daily maps of Sea Level Anomaly (SLA) from AVISO/CMEMS multimission satellites (0.33º x 0.33º and 0.25 x 0.25º Mercator grid products); and (ii) Along-track SLA from the pulse-limited Envisat RA-2 (18 Hz equivalent to a measurement distance between two consecutive along-track measurements of ~390 m), and the delay-Doppler (commonly known as SAR) CryoSat-2 SIRAL (20 Hz: ~350 m) and Sentinel-3A SRAL (80 Hz: ~87 m). The comparison between the gridded maps of monthly SLA and the tide gauges in the Gulf of Cadiz gave a level of agreement in terms of correlation coefficient (r) between 0.80 and 0.85. Improved along-track coastal altimetry products in the Strait of Gibraltar from Envisat RA-2 based on ALES reprocessing and improved geophysical corrections, showed rmse values ranging between 11.8 cm (ascending orbit in the western side of the Strait) and 13.4 cm (descending orbit in the eastern side). The validation of CryoSat-2 SIRAL (SAR mode) in the Gulf of Cadiz using a tide gauge not affected by water river discharges (Huelva station) gave rmse values ranging between 11.4 cm (3-km distance to land) and 6.4 cm (20-km distance). Finally, the preliminary validation of Sentinel 3-A SRAL in the Gulf of Cadiz shows a mean rmse of ~7.0 cm (no SSB applied) in the coastal strip (20 km from land). We will also present some of the main results and conclusions obtained after the scientific exploitation of the altimetry products analysed: (i) Improved estimates of the seasonal cycle in the Gulf of Cadiz; (ii) Effect of heavy water river discharge to the sea level in the estuary mouth of the Guadalquivir River; (iii) Cross-strait sea level variability in the Strait of Gibraltar.

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Contribution of 25 Years of Radar Altimeter Climate Data Record Towards Quantifying Global Geocentric Sea-Level Rise Over the Past Seven Decades

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Under an increasingly warmer Earth and the corresponding ablation of the world's ice reservoirs, accurately measuring relative and geocentric sea-level rise, and understanding its geophysical causes to improve the fidelity of sea-level projections at regional scales, is a significant scientific and societal problem facing mankind. Satellite radar altimeter missions have been providing continuous and near-global climate data record in accurate geocentric sea level measurements since 1991 for 26 years and counting. In contrast, globally sparsely located tide gauges have long-term (>50 years) records, but are susceptive to vertical land motion (VM) at tide gauge benchmarks as only a limited set of tide gauges have robustly collaborated GNSS receivers. The tide gauges are also not optimally geographically located to enable the estimation of spatially varying global mean sea-level rise trends, and plausibly sea-level acceleration.

This study intends to address the scientific questions: (1) can the 26+ year radar altimetry climate data record definitively separate the sea-level trends from other signals such as unmodeled interannual or longer oceanographic, tidal and atmospheric signals, acceleration if any, and instrument (altimeter and radiometer) drifts or corrections due to temperature and oscillator drifts? And (2) Can the 26+ year radar altimetry climate data record contribute, and to what extent, to the quantification of global sea-level rise during the last seven decades, using a novel sea-level reconstruction algorithm to separate vertical motion at global tide gauge benchmarks from the geocentric sea-level trend? Here we will present our findings, including our statistical assessments on the feasibility of separating the global sea-level trends, and other signals, including the hypothesized existence of sea-level accelerations at global and regional scales.

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Monitoring Topography of Intertidal Zones Using Satellite Radar Altimetry

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Radar altimetry was initially designed to measure the marine geoid. Thanks to the improvement in the orbit determination from the meter to the centimeter level, this technique has been providing accurate measurements of the sea surface topography over the open ocean since the launch of Topex/Poseidon in 1992. In spite of a decrease in the performance over land and coastal areas, it is now commonly used over these surfaces. This study presents a semi-automatic method that allows us to discriminate between acquisitions performed at high tides and low tides. The performances of four radar altimetry missions (ERS-2, ENVISAT, SARAL, and CryoSat-2) were analyzed for the retrieval of the intertidal zone topography in coastal bays such as Arcachon, Mont Saint Michel and Fundy Bays.

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Sea level Change since 2005: Importance of Salinity

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Sea level rise is one of the most important consequences of the actual global warming. Since 1993 (over the satellite altimetry era) global mean sea level has been rising at rate faster than previous decades. This rise is expected to accelerate over the coming decades and century. At global scale, sea level rise is caused by a combination of freshwater increase from land ice melting and land water changes (mass component) and ocean warming (thermal expansion). Estimating the causes is of great interest not only to understand past sea level changes but also to validate projections based on climate models. In this study, we investigate the global mass contribution to recent sea level changes with an alternative approach based on the freshwater budget of the ocean. We estimate the global ocean freshening from unprecedented amount of salinity measurements from Argo floats for the past decade (2005-2015) and correct it for the freshwater input from sea ice melt estimated from the PIOMAS reanalysis. From this we deduce the freshwater input into the ocean from land and atmosphere. We compare our results to the ocean mass inferred by GRACE data and based on a sea level budget approach. Our results bring new constrains on the global water cycle (ocean freshening) as well as on the global ocean mass directly inferred from GRACE data.

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Arctic Freshwater Fluxes from Satellite Altimetry and Earth Observation Data

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The ArcFlux project aims to determining the largest component to the Arctic Freshwater budget, namely the contribution from large rivers, glaciers as well as in-out flow of freshwater through the ocean pathways.

The main objectives of the project is to: Identify the major challenges associated with estimation of the Arctic Freshwater budget and Explore, develop and validate different approaches to address the identified challenges and enhance current approaches to compute the freshwater budget in the Arctic and compute a multi-year assessment of the Arctic freshwater budget based on the developed methodology. Finally the obtained results will be evaluated and the project will develop a scientific roadmap for future research activities in this domain of estimating the FWB of the Arctic Ocean.

Arcflux is supported in 2017 and 2018 within the ESA CLIC initiative which Is a part of the support to Science Elements framework

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Final Results from GOCE++ Dynamical Coastal Topography and Tide Gauge Unification Using Altimetry and GOCE.

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The major results from the ESA – GOCE ++ project on the potential of ocean levelling as a novel approach to the study of height system unification taking the recent development in geoid accuracy trough GOCE data into account. The suggested investigation involves the use of measurements and modelling to estimate Mean Dynamic Topography (MDT) of the ocean along a coastline which contributes/requires reconciling altimetry, tide gauge and vertical land motion. The fundamental use of the MDT computed using altimetry, ocean models or through the use of tide gauges has values of between -2 and +1 meters at different points in the ocean. However, close to the coast the determination of the MDT is problematic due to i.e., the altimeter footprint, land motion or parameterization/modelling of coastal currents.

The presentation also outlines a new addendum to the project on the use of GPS reflectometry as Coastal tide gauge and the correspondence with SAR altimetry from Cryosat-2 and Sentinel-3

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A New OGMOC Mean Dynamic Topography Model – DTU17MDT

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Within the ESA supported Optimal Geoid for Modelling Ocean Circulation (OGMOC) project a new geoid model have been derived. It is based on the GOCO05C setup though the newer DTU15GRA altimetric surface gravity has been used in the combination. Subsequently the model has been augmented using the EIGEN-6C4 coefficients to d/o 2160.

The new DTU17MDT has been derived using this new geoid model and the DTU15MSS mean sea surface. Compared to other geoid models the new OGMOC geoid model has been optimized to avoid striations and orange skin like features. Finally, the filtering was re-evaluated by adjusting the quasi-gaussian filter width to optimize the fit to drifter velocities. The results show that the new geodetic MDT improves the resolution of the details of the ocean circulation

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A Combined Mean Dynamic Topography Model – DTU17cMDT

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Within the ESA supported Optimal Geoid for Modelling Ocean Circulation (OGMOC) project a new geoid model have been derived. It is based on the GOCO05C setup though the newer DTU15GRA altimetric surface gravity has been used in the combination. Subsequently the model has been augmented using the EIGEN-6C4 coefficients to d/o 2160. Compared to the DTU13MSS, the DTU15MSS has been derived by including re-tracked CRYOSAT-2 altimetry also, hence, increasing its resolution. Also, some issues in the Polar regions have been solved. The new DTU17MDT has been derived using this new geoid model and the DTU15MSS mean sea surface. Compared to other geoid models the new OGMOC geoid model has been optimized to avoid striations and orange skin like features. The filtering was re-evaluated by adjusting the quasi-gaussian filter width to optimize the fit to drifter velocities. The results show that the new MDT improves the resolution of the details of the ocean circulation. Subsequently, the drifter velocities were integrated to enhance the resolution of the MDT. As a contribution to the ESA supported GOCE++ project DYCOT a special concern was devoted to the coastal areas to optimize the extrapolation towards the coast and to integrate mean sea levels at tide gauges into that process. The presentation will focus on the coastal zone when assessing the methodology, the data and the final model DTU17cMDT.

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Seamless Transition from LRM to SAR in the Arctic Ocean

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Conventional altimetry from ERS-1/ERS-2 and ENVISAT provides LRM altimetry in the Arctic Ocean since 1991 which have enabled us to derive a continuous record within the ESA sea level CCI initiative for 20 years up to latitude 82.

With the launch of SAR altimery onboard Cryosat-2 and with the availability of SARAL/ALtiKA Ka band altimetry two new sensors providing accurate the sea level mapping in the Arctic Ocean has been available since 2010.

Extending the sea level time series derived with LRM altimetry with SAR sea level time series in the Arctic Ocean is far from trivial. The first results from studies indicate that the difference in spatio-temporal coverage of the two sensors and the possibility to discriminate sea level within leads using SAR gives a spatially varying bias between the two sensors depending on ice concentration.

Another problem for the combination of the time series is the fact that Cryosat-2 does not carry a radiometer. Subsequently care has to be taken to which corrections are applied to the LRM and SAR altimetry datasets, respectively. Our initial finding is that spatial averaged data (and the related timeserie) from Cryosat-2 is lower than the corresponding time series for ENVISAT in the overlapping period during 2010 and 2011. Trying to integrate and extend the sea level time series in the Arctic Ocean with SARAL/AltiKa since 2013 has the further complication that the Ka band vs the Ku band altimeter has different scattering positions in the ice-column. In this presentation we will present our results to compute and quantify the inter-satellite biases between ENVISAT Cryosat-2 and SARAL/AltiKa in the ice-covered parts of the Arctic Ocean.

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Sea Level Anomalies and Mesoscale Activity Using Altimetry along the African Coats in the Eastern Tropical Atlantic Ocean (OSTST Alti-ETAO Project)

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The equatorial region, near the coast, represents a major contributor to the ocean/atmosphere/land heat and water fluxes, controlled by SST and the oceanic dynamics. The eastern tropical Atlantic ocean (ETAO, 35°S-20°N ; 25°W - African coast) region remains little studied. This region also encompasses a large-range of peculiar dynamics: large-scale zonal equatorial currents, strong coastal currents, equatorial and coastal trapped waves, the presence of both equatorial and near-coastal upwelling cells, gyre-like structures with the presence of the Guinea and Angola domes (Schott et al, 2004).

In this area, there are few in-situ measurements and the time coverage of these data is not better. Since 1993 sea level anomaly (SLA) are routinely measured using high-precision satellite altimetry (Topex/Poseidon, Jason-1/2, …) with this year, the anniversary of 25 years of progress in Radar Altimetry. While spatial altimetry has enabled us to highlight the regional variability of mesoscale dynamics, it still provides incomplete information in coastal areas in the first 25 km from the coasts, especially due to the perturbation of radar echoes by the continents (land, island, etc.). In the OSTST Alti-ETAO project, we studied the meso-scale dynamics using different altimetry sea level anomaly (SLA) products: AVISO gridded product (1/4°) and the coastal X-TRACK product from CTOH (LEGOS) based on Jason1-2 altimeters (Birol et al, 2016); but also, validate SLA data of the NEMO model (from LEGOS) in this region. We used also the tide gauge (TG) data available in the ETAO region for the validation of the altimetry and model SLA along the coast.

The comparison between the coastal altimetry along-track data (X-TRACK last reprocessing), AVISO gridded product, the NEMO model and TG data using different statistical criteria depends on the geographical position along the ETAO coasts. Near the coasts of Senegal and the Gulf of Guinea, we note a good agreement, in terms of correlation and quadratic errors (RMS), between the X-TRACK coastal altimetry data (closed to the tide gauge position and not in the first 10 km from the coast), the NEMO model data and tide gauge data. On the other hand, near the Namibian and South African coasts, where tide gauge data appear to be better in terms of time cover, low correlations and more significant quadratic errors are found between the X-TRACK coastal data, NEMO model and tide gauge data. This weak agreement could be related to the higher oceanic and atmospheric variability in the Benguela upwelling system not detected by altimetry and the geographic location of the TG relative to the altimetry data. We also show that, for points (altimetric and model) distant to the coast (several hundred km), the correlation is good with low rms, between the Pointe Noire TG, the altimetry products and the model data, which is aptly linked to the equatorial waves which propagate from the equator to the coasts, in this region. This is not the case in the two upwelling regions of Senegal and Bengela.

Studies are also underway at LEGOS to estimate the influence of the tide correction in this region, using the regional ocean dynamics numerical model T-UGOm based on unstructured meshes. (Carrere et al. 2012).

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CryoSat Interferometer Performance after 8 Years in Orbit

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The main payload of CryoSat is a Ku-band pulsewidth limited radar altimeter, called SIRAL (Synthetic interferometric radar altimeter). When commanded in SARIn (synthetic aperture radar interferometry) mode, through coherent along-track processing of the returns received from two antennas, the interferometric phase related to the first arrival of the echo is used to retrieve the angle of arrival of the scattering in the across-track direction. In fact, the across-track echo direction can be derived by exploiting the precise knowledge of the baseline vector (i.e. the vector between the two antennas centers of phase) and simple geometry.

In order to monitor the performance of the CryoSat interferometer along the mission, in orbit calibration campaigns following the approach described in [1] have been periodically performed about once a year.

The end-to-end calibration strategy for the CryoSat interferometer, described in [1], uses the ocean surface as the known external target. In fact, the interferometer can be used to determine the across-track slope of the overflown surface and the slope of the ocean surface can be considered as known starting from the geoid. Denoting by β the across-track slope of the ocean and assuming that the knowledge error of the geoid slope is negligibly small, β can be compared with the across-track slope derived from CryoSat SARin Level1b products which results in $\beta'=\eta(\theta-\chi)$ where η is a geometric factor, θ is the angle of earliest arrival measured by the CryoSat interferometer and χ is the baseline roll angle. By comparison of the expected across-track slope β and the measured across-track slope β', the accuracy and the precision of the angle of arrival θ measured by the CryoSat interferometer can be assessed. It is worth noticing here that the accuracy of the measured across-track slope β' is also dependent on the knowledge of the baseline orientation. As discussed in [1], starting from β and β' a calibration function $F(\theta)$ for the angle of arrival can be computed.

In our analysis, the accuracy (i.e. the closeness of the measurement to the true value) and of the precision (i.e. the closeness of agreement among a set of measurements) of the CryoSat interferometer have been assessed starting from the residual errors on the measured angle of arrival, that have been obtained after compensation of the calibration function $F(\theta)$.

One of the contributions to the inaccuracy of the angle of earliest arrival measured by the CryoSat interferometer is expected to arise from uncorrected thermal deformation of the star tracker-bench-antenna assembly. A first assessment of this contribution will be given starting from the analysis of the roll mispointing angles returned by the Star Trackers mounted at each side of the antenna bench.

[1] Galin, N.; Wingham, D.J.; Cullen, R.; Fornari, M.; Smith, W.H.F.; Abdalla, S., "Calibration of the CryoSat-2 Interferometer and Measurement of Across-Track Ocean Slope," in Geoscience and Remote Sensing, IEEE Transactions on , vol.51, no.1, pp.57-72, Jan. 2013

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CryoSat SIRAL: Instrument Performance after 8 Years of Operations

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The main payload of CryoSat is a Ku band pulsewidth limited radar altimeter, called SIRAL (Synthetic interferometric radar altimeter). Due to the fact that SIRAL is a phase coherent pulse-width limited radar altimeter, a proper calibration approach has been developed. In fact, not only corrections for transfer function, gain and instrument path delay have to be computed (as in previous altimeters), but also corrections for phase (SAR/SARIn) and phase difference between the two receiving chains (SARIN only). To summarize, SIRAL performs regularly four types of internal calibrations:

- CAL1 in order to calibrate the internal path delay and long-term power drift.
- CAL2 in order to compensate for the instrument IF transfer function.
- CAL4 to calibrate the interferometer.
- AutoCal, a specific sequence used to calibrate the gain and phase difference for each AGC setting.

After about 8 years of operational activity of the CryoSat satellite, the performance of the SIRAL instrument are revealed to be in line or better than the expected one.

In fact the calibration products, that have been designed to model a wide range of imperfections of the instrument, can be analyzed to highlight whether and how the instrument is changing over the time also as function of its thermal status. It is worth underlining here that each variation of the instrument measured by the calibration data is compensated in the Level1 processing.

Inspecting the temporal evolution of the calibration data, SIRAL has been verified to be stable during its life. The performance of the SIRAL will be presented together with the outcomes of the stability analysis on the calibration data, in order to verify that the instrument has reached the requirements and that it is maintaining the performance over its life. Moreover, in-depth analysis of the calibration corrections revealed how the instrument depends on its temperature and on the not-sun-synchronous orbit of the satellite.

In order to gain knowledge on the calibration corrections (i.e. the instrument behavior) and to verify whether the current calibration plan is able to provide sufficiently accurate corrections for the instrument acquisitions, ad-hoc calibration cycles for CAL1 and CAL2 were commanded in the last years. In this abstract, the outcome of the analysis of the calibration corrections generated during these activities will be also given.

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A Validation Dataset For CryoSat Sea Ice Investigators

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The CryoSat-2 mission with its innovative Synthetic-Aperture Radar Altimeter (SIRAL) has produced sea ice thickness data of unprecedented accuracy and regional coverage.

Over the same period ESA's CryoVEx and NASA IceBridge validation campaigns have been collecting a unique set of coincident airborne measurements in the Arctic. The CryoVal-SI project has collated the campaign data and selected the CryoSat ground tracks which have the best coverage by coincident campaign data . The campaign data were processed and resampled to coincident CryoSat footprints to make them easier to utilise. The resulting validation dataset provides an independent metric that can be used to objectively evaluate any experimental changes or refinements to the CryoSat data processing that a user may wish to test.

This valuable resource is in itself an output of the CryoVal-SI project which is made openly and freely available to the scientific community. We will describe the composition of the validation dataset, summarising how it was processed and how to understand the content and format of the data. We will also explain how to access the data and the supporting documentation

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How GNSS IPPP Positioning Technique Can Help Space Altimeter Missions?

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The aim of this presentation is to give a review on the interest of the GNSS IPPP Positioning technique in the frame of space altimeter missions. IPPP consists in calculating precise positions of single receivers using GNSS phase observations with fixed integer ambiguities. This technique is an alternative to the classical differential approach and has been extensively used by several authors in the past few years. They all have in common the tracking of a floating mobile along the track of an altimeter satellite and the use of the CNES GINS software coupled with the CNES-CLS IGS Analysis Center satellite orbit and clock products. However the field campaigns were as diverse as the open ocean, coastal area, along rivers and on lakes. The corresponding results are recalled as well as how IPPP solutions can be derived. The future capabilities of the Galileo constellation in this context are discussed

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Developments in Sentinel-3 Altimetry for Sea Ice

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This presentation reviews the progress to date on the evolution of the operational Sea Ice processing for the Sentinel-3 Altimeter. Experience gained from the investigation of the S3 data acquired over Arctic sea ice data during 2 winters has led to improvements in the ground segment processing. We identify algorithm and parameter changes and their impact on measurement results. We will summarise the current status and present some further improvements recommended for future upgrades. We will compare and contrast implementation differences between Sentinel-3 and CryoSat-2 and illustrate the impact on results.

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25 years of Caspian Sea Level Fluctuations and its Regional Variability

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The Caspian Sea is the largest inland water body of the world and is located at the border between Europe and Asia. During the last century sea level fluctuation of more than 2.5 m have been observed. Since 1993 the sea level of the Caspian Sea has been monitored by satellite altimeters. Here we study the fluctuations of the mean sea level and of its regional variability exploiting the multi-mission altimeter data set of the last 25 years. The mean sea level is governed by the balance between river discharge (mainly river Volga) and net evaporation. During the altimetry era it has fluctuated by more than 1.5 m and is decreasing since 2005 by about 10 cm/year. Especially in the shallow northern part of the Caspian Sea the drop of the sea level is causing changes of the coastline.

Overlaid to these mean sea level fluctuations there are also regional patterns of change. They can in part be attributed to changes of river run-off and related density changes. The spatio-temporal characteristics of regional variability are further investigated. Special focus will be on changes close to the coast.

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Vertical Land Motion Determined by Satellite Altimetry and Tide-Gauge Data in Fennoscandia

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Present-day vertical land motion in Fennoscandia reaches values up to around 1 cm/year. The primary cause of the uplift is Glacial Isostatic Adjustment , i.e., the ongoing response of the Earth and the ocean to the melting of late-Pleistocene ice sheets. Additional signals caused, e.g., by the elastic rebound from contemporary melting of glaciers, tectonics, and hydrology contribute less.

The relation between relative sea-level change (Sdot), change in the sea surface height (Ndot), and vertical land motion (Udot) is given by Sdot = Ndot – Udot. All three quantities can be observed directly by means of tide gauges, satellite altimetry, and Global Navigation Satellite Systems (GNSS), respectively. Alternatively, Udot may be estimated from observations of Sdot and Ndot.

In the present study, we combine satellite altimetry and tide-gauge data to determine vertical land motion at tide gauges in Fennoscandia. Considering the discrepancies in the spatial sampling of conventional altimeters, where the mean distance between conventional altimetry sites and tide gauges along the Norwegian coast is 53 km, we take advantage of the CryoSat-2 geodetic orbit. The European Space Agency's CryoSat-2 satellite is the first to carry a synthetic aperture interferometric radar altimeter, resulting in higher range precision and along-track resolution. This allows us to get closer to the coast, with observations of the sea surface at the tide-gauge stations as a main benefit when combining altimetry and tide-gauge data. In turn, we compare the estimated vertical land motion rates with the independent semi-empirical land uplift model NKG2016LU for the Nordic-Baltic region, based on GNSS and levelling

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Impact of the Assimilation of High-Resolution and High-Frequency Data in a Regional Model

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Mercator-Ocean has developed a regional forecasting system at 1/36° (~3km) resolution over the North East Atlantic (IBI: Iberia, Biscay and Irish), taking advantage of the recent developments in NEMO. The model was forced by ECMWF (European Centre for Medium-Range Weather Forecats) products (every 3 hours) including the atmospheric pressure. In addition to atmospheric forcing, the model includes astronomical tidal forcing. This regional forecasting system uses boundary conditions from the Mercator-Ocean global system (with data assimilation, 1/12° resolution). The assimilation component of the Mercator Ocean system, is based on a reduced-order Kalman filter (the SEEK or Singular Extended Evolutive Kalman filter). An IAU method (Incremental Analysis Updates) is used to apply the increments in the system. The error statistics are represented in a sub-space spanned by a small number of dominant 3D error directions. A 3D-Var scheme corrects for the slowly evolving large-scale biases in temperature and salinity. The data assimilation system allows to constrain the model in a multivariate way with Sea Surface Temperature, together with all available satellite Sea Level Anomalies, and with in situ observations, including ARGO floats temperature and salinity measurements. The background SLA field accounts for the high frequency signal determined by the model and the forcing by atmospheric pressure.

In this study we show the impact of the assimilation of altimetry high-resolution (5Hz) data unfiltered from high atmospheric frequencies. Altimetry data assimilated then contain the effect of atmospheric pressure and wind on the SLA unlike conventional data used in operational systems. We compare ocean analysis and forecasts obtained with those two different SLA data sets OR we analyse the impact of using those high resolution and high frequency observations.

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The Multi Observation Thematic Assembly Centre of the Copernicus Marine Environment Monitoring Service

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Complementary to ocean state estimate provided by modelling/assimilation systems, a multi observation-based approach is available through the MULTI OSERVATION (MULTIOBS) Thematic Assembly Center (TAC) of the Copernicus Marine Environment Monitoring Service (CMEMS).

CMEMS MULTIOBS TAC proposes products based on satellite & in situ observations and state-of-the-art data fusion techniques. These products are fully qualified and documented and, are distribution through the CMEMS catalogue (http://marine.copernicus.eu/services-portfolio). They cover the global ocean and, physical and biogeochemical (BGC) variables. They are available in Near-Real-Time (NRT) or as Multi-Year Products (MYP) for the past 10 to 25 years.

Satellite input observations include primarily altimetry but also sea surface temperature, sea surface salinity as well as ocean color. In situ observations of physical and BGC variables are from autonomous platform such as Argo, moorings and ship-based measurements. Data fusion techniques are based on multiple linear regression method, multidimensional optimal interpolation method or neural network.

MULTIOBS TAC provide the following products at global scale:

☐ 3D temperature, salinity, geopotential height and geostrophic current fields, both in NRT and as MYP (Guinehut et al., 2012; Mulet et al., 2012);

☐ 2D sea surface salinity and sea surface density fields, both in NRT and as MYP (Buongiorno Nardelli; 2012; Droghei et al., 2016);

☐ 2D total surface and near-surface currents, both in NRT and as MYP (Rio et al., 2014; Rio et al., 2016);

☐ 3D Vertical velocity fields as MYP (Buongiorno Nardelli et al., 2018);

☐ 2D surface carbon fields of FCO2, pCO2 and pH as MYP (Sommer et al., 2017);

☐ Nutrient vertical distribution (including Nitrates, Phosphates and Silicates) profiles as MYP (Sauzède et al., 2017);

☐ 3D Particulate Organic Carbon (POC) and Chlorophyll a (Chl-a) fields as MYP (Sauzède et al., 2016).

Furthermore, MULTIOBS TAC provides specific Ocean Monitoring Indicators (OMIs), based on the above products, to monitor the global ocean 3D hydrographic variability patterns (water masses and currents) and the global ocean carbon sink.

MULTIOBS system, products and performances are described through various applications: system intercomparison, ocean state estimate, mesoscale eddies studies, water mass formation.

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Tailored Altimeter Products for Assimilation Systems (TAPAS products)

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In 1998, first Level3, user friendly altimeter products have been developed with support from CNES and delivered to the users on AVISO+. The Level3 processing includes a homogenisation of the SLA for the different altimeters (i.e. reduction of the global and regional biases), allowing the users to directly use the products without any pre-processing. They are widely used for different applications, including assimilation in numerical models. Since 2008, such products are generated and disseminated by the Copernicus Marine Service (CMEMS; previously MyOcean during its demonstration phase). In this context, the yearly "Tailored Altimeter Products for Assimilation Systems (TAPAS)" working group was set up to strengthen the link between the altimeter and model communities. One of the objectives of these meetings is to understand the specific needs from modelers to tailor the Level3 products, in terms of physical content and spatial resolution. In that way, since 2013 a new Level3 tailored product for assimilation purpose was introduced in the MyOcean/CMEMS Catalogue. It allows the user to change the physical content of the altimeter measurement in consistency with the model capabilities and characteristics, thus considerably improving the results of the assimilation of the altimeter measurement into the models. Because of the constant evolution of the numerical models, the TAPAS WG remains a meeting to maintain the information flux between data producer and users and allow us to define the next generation of Level3 product. New altimeter techniques (i.e. SAR mode measurement) allow us to observe smaller spatial scales. On another hand, models resolution is increasing, making the assimilation of these finer scales a challenge.

We present in this paper the TAPAS products and their impact for numerical models

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An OSSE to Quantify the Reliability and the Accuracy of Automatic Eddy Detection Performed on Gridded Altimetric Product.

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Automatic eddy detection algorithms are widely used to identify and track coherent structures on gridded altimetric products (SLA, ADT or surface velocities). However, these gridded products have significant spatial and temporal limitations. Even if daily maps are provided, the frequency of the altimetric tracks is too low to follow accurately the dynamical evolution of eddies below a characteristic time scale of 6-10 days. On one hand, a meso scale eddy may totally disappear between consecutive maps if altimetric tracks do not cross the structure for several days. On the other hand, the optimal interpolation technique which is used to fill the gaps between the altimetric tracks may induce ghost eddies which are not real. In order to provide a quantitative assessment of these errors made on the eddy detection, we performed an Observing System Simulation Experiment (OSSE). We used the outputs of one year of numerical simulations (NEMO MEDRYS1V2 gridded at ~1/12°) in the Mediterranean Sea for the reference fields. From this reference SSH, synthetic gridded products were constructed, in a similar way as the CMEMS/DUACS multi-mission altimeter gridded SLA product (formerly distributed by AVISO). First, a real constellation of four satellites was used to build a synthetic altimetric signal along each track. Then, gridded maps of SLA and ADT were reconstructed using an optimal interpolation scheme of CLS. This scheme was optimized for the Mediterranean basin meso-scale variability specifically for this study. Finally, the surface geostrophic velocity fields were derived.

Then we applied the AMEDA eddy detection algorithm on both the reference and the OSSE fields. We were then able to identify three types of eddies: the « missed », the « ghost » and the « detected » ones. The missed (ghost) eddies correspond to the coherent structures detected (not-detected) in the reference field and not-detected (detected) in the OSSE while the « detected » eddies are the one located both in the reference and the OSSE field. Our statistical analysis shows that the percentage of missed and ghost eddies could vary from 30% to 2% depending on their size and intensity: large and intense structures are more reliable than small or weaker ones. Besides, we built a density parameter, quantifying the number of altimetric tracks inside a given eddy during a given period. This dimensionless parameter is a first proxy to quantify the reliability (i.e. probability to be a ghost) and the accuracy of the estimated size and intensity of any detected eddy in comparison with the reference one. Such estimation of the reliability and the accuracy of the detected eddies may improve the near real time monitoring of large meso scale eddies and the statistical analysis of long term series.

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Coastal Currents In The Eastern Gulf of Tehuantepec, Mexico

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We study the seasonal and interannual variability of the flow along the eastern shelf of the Gulf of Tehuantepec. We validate coastal altimetry sea level processed by CTOH using tide gauge and hydrographic data. Results indicate that this coastal product measures well both the seasonal and the interannual time scales. A 12-year time series of altimetry-derived currents reveal new details of the seasonal cycle in the eastern Gulf of Tehuantepec: currents flow poleward from October to February and equatorward from April to August. Spectral analysis reveal that mesoscale processes are at least equally energetic as the seasonal mean flow. The combination of both determines to a major extent thel variability of the coastal currents

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On the Use of Eddies Detected from Surface Drifters to Quantitatively Validate and Compare the Mesoscale Eddy Atlases Constructed from Altimetry Maps.

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Since 1992, satellite altimeters recorded dynamical topography that revealed, among other phenomena, the mesoscale dynamics of the World Ocean. Using the resulting maps, a number of studies have estimated eddies and their trajectories at mid to high latitude applying various automatic eddy detection algorithms. However, the quantitative comparison of the resulting atlases is a tedious task. Here, we present a protocol based on an eddy atlas obtained from the identification of Loopers in the Global Drifter Program to study the efficiency of each method to detect and track mesoscale eddies. This comparison shows that this efficiency can drastically change depending on the algorithm used and that the trajectory reconstruction can be limited without the consideration of merging and splitting events

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In Situ and Satellite Altimetry Ocean Currents in a Biologically Productive Region of the Patagonia Continental Shelf, Argentina

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The wide Patagonian shelf contains one of the most biologically productive areas of the world ocean. The southern region of the Patagonian shelf harbors the spawning area of one of the most important commercial species from an economical point of view: the argentine hake, whose larvae are mostly located in the bottom layer. According to recent studies, when the hake of the larvae reach a certain size, they drift towards a growing area located in the inner part of San Jorge Gulf, by taking advantage of bottom currents. Knowledge of currents and its variability is therefore a key point to improve the management of this economical resource. In this context, a 5-months long time series of ocean currents collected at 44.7°S and 63.7°W is analyzed in this work. Data were recorded by a 300 kHZ upward-looking ADCP deployed within the French-Argentine CASSIS-Malvinas project from May to October 2016 (http://www.cima.fcen.uba.ar/malvinascurrent/es/).

The deployment is located near a well-documented tidal frontal system that is highly productive. Therefore, the study of the water movement in this area is essential for better understanding biological processes. Mean velocities for the period of measurement are of the order of (4.7 ± 0.1) cm/s. The upper layer (up to ~45 m depth) presents mean velocities to the NE while the lower layer in the opposite direction, in agreement with numerical models outputs.

Tidal-filtered in situ currents show a dominant direction in the NE-SW direction, coherent with local bathymetry. The baroclinic component dominates the circulation as it explains 63.5% of the total variance. The first mode of the Empirical Orthogonal Functions (EOFs) of the data shows a sign change between the surface and the bottom for both the zonal (u) and meridional (v) components. The first mode of u(v) explains 70.8%(45.2%) of the total variance and presents oscillations with a 4-days (14-days) period, generating changes in the direction of the velocity vectors, that present opposite directions above and below 45m (30m) depth.

Preliminary results of the comparison between in situ data and L4 gridded satellite geostrophic currents provided by marine Copernicus (http://marine.copernicus.eu) show significant but low vector correlation coefficients (0.19) and a root mean square error of 8cm/s when in situ data is low-pass filtered with a cut-off period of 20 days. Comparison with other satellite products is on-going.

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Synergy between HF Radar and Altimetry in the SE Bay of Biscay

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The combination of different measuring systems in overlapping areas has proven to be a suitable approach to improve ocean monitoring and operational forecasts. The synergy between HF radar and altimetry data, especially in coastal areas, is one example. This study is focused on the South East Bay of Biscay (SE-BoB), an area composed of a narrow shelf and a slope with submarine canyons and an abrupt change in the orientation of the coast. These features, and their effects on the currents, hinder the characterisation and measurement of the different oceanic processes in this area. With the aim of achieving a better understanding of the local hydrodynamics and the limitations of the two measuring systems, an analysis of the information contained in different data sets has been carried out.

To this end, we use data from a 4.5 MHz HF radar system, which provides hourly current fields with a resolution of 5 km, and SLA data from the Jason-2 satellite's altimeter track 248, with 7-km along-track resolution of a 10-day revisit time. HF radar and altimetry data have been compared statistically in order to obtain a better diagnosis of the agreement of both systems in measuring surface currents. Besides, the main mesoscale, seasonal and interannual processes observed by both systems have been qualitatively studied over the period 2009-2015. Four mesoscale eddies have been isolated and analysed by comparing altimetric across-track currents with the radar current fields. Another four intense Iberian Poleward Current events have been also isolated and characterized, using also SST data.

Additionally, the comparison of surface currents remotely measured with available in-situ datasets has been performed. For this purpose, ADCP and CTD data from oceanographic campaigns and from two slope moorings have been used. The comparisons in the water column have enabled the analysis of the coherence between the surface and subsurface ocean processes in the area.

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On the Approximation of the Inverse Error Covariances of High Resolution Satellite Altimetry Data

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High-resolution (swath) altimeter missions scheduled to monitor the ocean surface in the near future have observation error covariances (OECs) with slowly decaying off-diagonal elements. This property presents a challenge for the majority of the data assimilation (DA) algorithms which were designed under the assumption of the diagonal OECs being easily inverted. We present a method of approximating the inverse of a dense OEC by a sparse matrix represented by the polynomial of spatially inhomogeneous differential operators, whose coefficients are optimized to fit the target OEC by minimizing a quadratic cost function. Explicit expressions for the cost function gradient and the Hessian are derived. The approximation is tested with an OEC model generated by the SWOT simulator and compared with a previously introduced methodology. Our approach is found to be more accurate and more general, highlighting its utility for operational efforts which seek to properly account for correlated errors in the forthcoming wide swath altimetry observations

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Study of a Mesoscale Eddy Using Drifters and Coastal Altimetry in the Bay of La Paz, Mexico.

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The Bay of La Paz is located at about 23°N in Northwest Mexico. It is the largest and deepest coastal body of the Gulf of California because of a marine depression located in its northern half with a recorded depth of 410 m. This is Cuenca Alfonso and it is a long-term monitoring and biogeochemical flux study site. The composition here is influenced by the water masses of the Gulf of California (GCW) and the Subtropical Subsurface (StSsW). Surface winds follow the seasonal monsoonal pattern of the Gulf of California: from the south-southeast in spring-summer and from the northwest in autumn-winter. Sea and land breezes acquire importance during spring and early summer and are able to influence the circulation inside the bay and in its vicinity. Different authors report the existence of a cyclonic eddy in the surface of this depression, promoting fertilization during the spring season. Here we describe a coastal eddy using drifter trajectories of the Global Drifter Program, from June and September 2004. Sea level slopes are characterized with the aid of coastal altimetry tracks from the ALES re-tracker. And to complete the picture sea surface temperature maps from the GHRSST project and wind statistics estimated from nearby meteorological stations are also included. We discuss the relevance of this mesoscale feature to understand variability observed in the time series being measured at Cuenca Alfonso

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CryoSat-2 On-going Cal/Val and Oceanographic Studies from Pole to Equator

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CryoSat-2 was planned as the European Space Agency’s first ice mission but its contributions to oceanographic studies are of significant benefit to the oceanographic community from pole to equator.

Data over all surface types are acquired by CroSat-2, including the global oceans where the altimeter operates mainly in conventional low-resolution-mode (LRM) but also in SAR (synthetic aperture radar) mode over a few regions. A dedicated operational ocean processor has existed for CryoSat-2 since April 2014. In addition, the same processing chain has recently been used to provide data for the full-length of CryoSat-2 operations (from November 2010 onwards). A new version of the processor has been in operation from November 2017 onwards.

Within the ESA funded CryOcean-QCV project, the UK's National Oceanography Centre (NOC) is responsible for routine quality control and validation of CryoSat Ocean Products. Activities include daily and monthly reports providing global assessments and quality control of Sea Surface Height Anomaly (SSHA), Significant Wave Height (SWH), backscatter coefficient (Sigma0) and wind speed, as well as a suite of validation protocols involving in situ data, model output and data from other satellite altimetry missions. This presentation will present some of the metrics and results obtained for CryoSat Ocean Products for SSHA, SWH and wind speed using data from tide gauges, wind and wave buoys, WaveWatch III wave model output, HF radar surface current data and comparisons with Jason-2 and Jason-3. Example metrics include SSHA along-track power spectra and the characterisation of offsets and variability regionally and in different sea states.

Looking forward comparisons of CryoSat-2 with Sentinel-3 data are now being planned and added to the suite of tools along with results poleward of ±66˚N and when CryoSat-2 is operating in SAR mode.

Finally, the utility of the data from CryoSat-2 for oceanographic studies will be demonstrated using sea surface height anomalies. We will present examples of the benefits for oceanographic studies using a Level 3 product, including investigations of propagating features (e.g. Rossby-type wave propagation).

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Malvinas Current at 44.7ºS: Analysis of its Variability

from in-situ Data and 25 years of Satellite Altimetry Data

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In the framework of the CASSIS project three tall moorings equipped with current-meters were deployed in a zonal section at 44.7ºS across the continental shelf-break of the Southwestern Atlantic between December 2015 and June 2017. The section is orthogonal to the Malvinas Current (MC) that flows northward in this location. This is the first time that a time series of the MC is recorded at this latitude. Previous measurements were made at 41ºS, being strongly affected by the proximity of the Brazil-Malvinas Confluence region. The 18-month twenty-day low pass filtered time series of in situ velocities obtained from the shallowest instruments are significantly correlated with geostrophic velocities obtained from a gridded altimetry product (r=0.8). The in situ velocity measurements present large oscillations (up to 50 cm/s in less than a week). These short-term oscillations are severely smoothed in the altimetry field. The large oscillations in the in-situ observations are coherent with the presence of multiple current jets and, during some events, of a strong, zonally oscillating jet. The altimetry data suggests that the MC broadens and strengths alternatively and that those changes are the result of the interaction with mesoscale activity on the eastern side of the MC. The analysis of the 25-years time series of altimeter data no significant trend in magnitude of the geostrophic velocity of the MC at this latitude

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Effect of Altimeter Data Assimilation on the Ecosystem Distributions in the Japan Sea.

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Altimeter data are indispensable for the better hindcasting and/or forecasting in the ocean. Many studies assimilating altimeter data have already improved physical model performance related to water temperature and salinity, but only a few studies could be related with the biological variables such as a chlorophyll-a concentration. In this study, the reproducibility of the chlorophyll-a concentration in a regional physical-ecosystem coupled model called DREAMS2 is investigated by comparing the simulation and the altimeter data assimilation. The analysis region is the southern part of the Japan Sea including the meandering of the Tsushima warm current and the formation of the mesoscale eddies. The physical part of the coupled model is described by Hirose et al. (2013) and the ecosystem part is the simple NPZD type of Onitsuka et al. (2007). The monthly means of the model chlorophyll-a concentrations are compared with the monthly satellite data by calculating spatial correlation coefficients. The correlations of chlorophyll-a concentration between the assimilation result and the satellite data are basically higher than the ones of the simulation. For example, in October 2005, the spatial correlations with the satellite (SeaWiFS) chlorophyll-a data to the simulation and the assimilation are 0.25 and 0.46, respectively. The higher correlations in the assimilation compared to the simulation are especially prominent in summer and autumn, but are modest in winter and spring. In summer and autumn, the dissolved inorganic nitrogen (DIN) concentration as the limiting factor is generally depleted at the surface layer of the Japan Sea but is occasionally provided for the growth of phytoplankton depending on the physical conditions such mixing and upwelling. The assimilated results are better resolved those conditions crucial to the ecosystem variation. Therefore, the altimeter data can contribute to the understanding of the nutrient and chlorophyll-a distributions by improving the position of the mesoscale eddies and the current velocity fields through assimilation in the southern part of the Japan Sea. The data assimilation linked to the ecosystem will be beneficial to fisheries research including fishing ground formation.

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Altimeter Assimilation with Offline Estimates of Non-Steric Sea Surface Height Variations

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Sea Surface Height (SSH) observations derived from satellite altimeter include steric and non-steric signals. The non-steric component is further divided into SSH variations due to global ocean mass change and non-steric response to atmospheric forcing, which are not properly taken into account in most ocean data assimilation systems. We developed an assimilation scheme for altimeter data, in which altimeter-derived SSH anomalies are assimilated after subtracting the non-steric component to estimate temperature and salinity in the ocean interior. The non-steric signal due to the global ocean mass change is estimated offline by taking misfit of altimeter-derived SSH and in-situ observation-based steric height anomalies. The wind-driven non-steric signals are diagnosed by bottom pressure anomalies from an ocean model used in the assimilation system. We applied this scheme to regional and global systems. It is shown that subsurface temperature bias and seasonal change of subarctic circulation are improved. Furthermore, the artificial circulation in the transition regions from where SSH observation data constrain the model to where data are not available is much reduced by improving the global ocean mass balance, leading to a better reproduction of the temperature and salinity fields in the Arctic Ocean

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Impact of Assimilated Altimetric Observations in the Mercator Océan Forecasting System.

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Altimetric observations are one of the main sources of information constraining oceanic model used to produce ocean forecasts and analysis in Mercator Océan. In addition to in situ and sea surface temperature data, Sea Level Anomalies (SLA) are assimilated with the knowledge of a surface reference, the Mean Dynamic Topography (MDT). The quality of Mercator Océan products highly rely then, on the availability and quality of SLA observations, and on the accuracy of the surface reference.

In order to quantify the impacts of the present network and recent changes in the constellation, Observing system experiments (OSEs) are conducted with the operational forecasting system. Dedicated tools like forecast skill, degrees of freedom of the system (DFS) and a detailed analysis of the differences between twin experiments, allowed to highlight the importance of the observations coverage and altimeter repetitiveness. We especially focus here on the recent assimilation of Sentinel3-A observations. We show the benefits of the assimilation of a fourth altimeter, here S3-A, which allows an additional forecast error reduction of 10% in explained variance.

Following the same methodology, we then present the impact of using an accurate observed MDT solutions on the model analysis and forecasts. Two experiments using two MDT solutions have been compared. It is shown that the MDT changes have impact not only on surface states but also on 3D temperature and salinity fields.

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Detection of Ships Using Sentinel-3A SRAL Altimeter Waveforms

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The detection of non-ocean scatterers over the sea surface by using pulse-limited satellite altimeters involves a series of challenging targets, such as icebergs, lighthouses and ships, which have been investigated in the literature. In particular, past works focused on the hyperbolic features observed in the thermal noise area of the received waveforms, in order to detect the presence of such non-ocean targets. Following previous analysis made with CryoSat-2 data, in this work we exploit the capabilities of Sentinel-3A SRAL delay-Doppler instrument for the detection and characterisation of ships. In particular, we analyse the shape of the waveforms at two along-track sampling rates: 20 Hz – 80 Hz, in order to investigate the effect of the two resolutions in the discrimination of ships. This analysis might help to investigate the possibility to estimate some geometric features of the detected vessels from the echoes returned by the altimeter. The presented approach offers the opportunity to: i) study the compatibility between the detected target(s) and the known ship traffic, by using the Automatic Identification System (AIS) data; ii) resolve ambiguities among multiple targets, by using two different along-track spatial resolutions, due to the different sampling rates. Ship traffic statistics, as introduced by the literature, may take benefit from the method described in this work, providing a contribution to improve the overall precision of such statistics. The Sentinel-3 mission used in this work will provide a constellation with global SAR coverage (S3A and the new S3B) and free accessibility to the data, with a potential enhancement to the estimation of the number and characteristics of the ships with respect to past literature approaches.

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Monitoring the Algerian Basin Through Glider Observations, Satellite Altimetry and Numerical Simulations During the ABACUS Projects (2014-2018)

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The Algerian Basin is a key component of the general circulation in the Western Mediterranean Sea. The presence of both fresh Atlantic water and more saline Mediterranean water gives the basin an intense inflow/ outflow regime and complex circulation patterns. Energetic mesoscale structures that evolve from meanders of the Algerian Current into isolated cyclonic and anticyclonic eddies dominate the area, with marked repercussions on biological activity. Despite its remarkable importance, this region and its variability are still poorly known and basin-wide knowledge of its meso- and submesoscale features is still incomplete. Studying such complex processes requires a synergistic approach that involves integrated observing systems. In recent years, several studies have demonstrated the advantages of combined use of autonomous underwater vehicles, such as gliders, with a new generation of satellite altimetry. In this context, we present the monitoring activities conducted in the Algerian Basin between September 2014 and May 2018, in the framework of several editions of the "Algerian BAsin Circulation Unmanned Survey - ABACUS" project. These activities were realized through the SOCIB (Balearic Islands Coastal Observing and Forecasting System) Glider Facility Open Access Programme and were supported by the Joint European Research Infrastructure network for Coastal Observatories (JERICO) Trans National Access (TNA), the SOCIB external access and the JERICO-NEXT TNA.

During the ABACUS missions, a total of 12 glider transects were carried out between the island of Mallorca and the Algerian coast, collecting Temperature, Salinity, Turbidity, Oxygen and Chlorophyll concentration high resolution data in the first 975 m of the water column. In situ data collection was supported by near real time remotely sensed data from different platforms over the Western Mediterranean Sea. In particular, gridded altimetry data provided by the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO), Sea Surface Temperature (SST) and Chlorophyll-a concentration (Chla) information from MODerate resolution Imaging Spectroradiometer (MODIS) data acquired by NASA were used to provide a large scale description of the dynamics and surface water masses. Glider surveys were always conducted along the groundtracks of operating altimetry satellites, i.e. SARAL/AltiKa and Sentinel-3, and were planned in order to get always the glider at sea during the satellites overflight. Furthermore, the adaptive sampling capabilities of the Slocum gliders also allowed to partially modify their tracks in order to investigate the oceanographic characteristics of interesting mesoscale structures identified through altimetry.

Here we report on comparative analyses of glider measurements with both co-located (SARAL/AltiKa and Sentinel-3) altimetric products, and CMEMS numerical simulations. Results show similar patterns for glider-derived dynamic heights and altimetric absolute dynamic topography. Even though larger discrepancies are observed near the Balearic and Algerian coasts, correlation coefficients between glider and satellite observations seem mostly to be affected by synopticity between remote sensed and in situ measurements.

We expect to apply this ocean observing strategy also for validating products provided by new generation altimeters that are designed to be better suited for coastal, mesoscale and submesoscale monitoring, such as the forthcoming wide-swath radar interferometer Surface Water and Ocean Topography (SWOT).

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Reconstruction of the West Spitsbergen Current Using a Combination of Observations from Satellite Altimetry, Numerical Model and In Situ.

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The West Spitsbergen Current (WSC) is of fundamental value for the Arctic because it is a major source of heat and is affecting Arctic air temperatures and sea ice conditions. Institute of Oceanology, Polish Academy of Sciences (IO PAS) recognizes the importance of the region by performing regular cruises to the WSC every July since 2000. Despite the large number of data collected, the IO PAS data represent only a temporal situation occurring in July. There are no data from other seasons and the frequency of measurement is too low to allow analysis of the dynamic process that is changing very fast with time, location and depth. Satellite altimetry provides high-quality data that can be used to study the variability of sea level and the surface geostrophic circulation. However, we do not know how these surface geostrophic currents relate to the deeper currents and how we could use altimetry to get currents in the deeper layers. The information about the vertical structure of currents is essential for the estimation of volume, salt and heat fluxes. The aim of this study is to investigate the relationship between the geostrophic surface currents, obtained from the altimetry, and deeper currents measured in situ by IO PAS along the WSC in 2000-2013. The relationship will be also analyzed using high-resolution ocean numerical model (NEMO), in order to inform about the spatial and temporal variability of the relationship along the current's pathway. The above analysis will provide information about the vertical structure of the WSC and its spatial and temporal variability. Another objective of this study is to use the obtained relationship, combined with the modelled vertical structure of the WSC, to extend timeseries of the WSC to other seasons. The results will allow to characterize the WSC variability from monthly to inter-annual timescales

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Impact of a New High Resolution Mean Dynamic Topography and its Associated Error on the Assimilation of Sea Level Anomaly Altimetry Data in Mercator Ocean Reanalyses at ¼° and 1/12°

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Mercator Ocean has recently produced in the framework of Copernicus Marine Environment Monitoring Service (CMEMS), a global eddy-resolving physical reanalysis GLORYS12V1 re-analysis (hereafter G12V1). This reanalysis covers the altimetry era (1993-2017) and is based on the current global high resolution CMEMS real-time forecasting system PSY4V3R1 with a horizontal resolution at 1/12 ° and 50 vertical levels. In parallel, a twin reanalysis GLORYS4V1 (hereafter G4V1) at ¼° (same parameterizations of the ocean model and the assimilation scheme) has been produced to potentially anticipate, given its lower cost of calculation, the problems occurring in G12V1 and to measure the impact of horizontal resolution.

Along track altimeter data (Sea Level Anomaly – SLA), satellite Sea Surface Temperature (SST), Sea Ice Concentration and in situ temperature and salinity (T/S) vertical profiles have been jointly assimilated in these two reanalyses. A “hybrid” Mean Dynamic Topography (MDT) has been also used as a reference for SLA assimilation. This hybrid MDT is based roughly on the CNES-CLS13 MDT with adjustments made using the GLORYS2V3 Mercator Ocean global reanalysis at ¼°, a geoid model based on GRACE and GOCE data and an improved Post Glacial Rebound (also called Glacial Isostatic Adjustment). The MDT is a very important component in the analysis system implemented by Mercator Ocean because it makes it possible to assimilate SLA altimetry data and it indirectly constrains the mean circulation of the model. The mean positions of the Gulf Stream, the Kuroshio or the North Atlantic Current are dictated by the fronts in the MDT. The mesoscale activity given by the SLA is superimposed, but the mean advection is greatly dependent on the MDT.

To improve the integration of altimetry observations, the average circulation represented by the systems, and to correct regional biases present in G4V1 and G12V1, a new hybrid high resolution MDT has been generated this last year using the observations currently available (latest versions of Mean Sea Surface and GOCE geoid) but also using the inter-annual high resolution simulation G12V1. It is proposed in this presentation to list the different biases still present in both reanalyses (sometimes G12V1 differs significantly from G4V1) and to show how this new MDT reduces these biases, in particular the excessive Antarctic Circumpolar Current freshening

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New Connections Across the Ecosystem Due to Transport of Anthropogenic Marine Debris By Ocean Circulation

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Increasing production of anthropogenic materials results in their accumulation in the environment. Complex composition of floating marine debris, scattered and poorly known debris sources and sinks as well as the complex dynamics of the oceanic and atmospheric boundary layers make tracking and quantitative assessment of debris very difficult tasks, both for observations and for models.

The tragic Great Tohoku Earthquake and Tsunami destroyed on March 11, 2011 more than 100,000 homes and generated large mass of floating marine debris (estimated 1.5 million tons), comparable with the full-year balance of the entire North Pacific. Originally thick mats of the Japan tsunami marine debris (JTMD) drifted eastward, dispersed and mixed with debris from general sources. JTMD started arriving in North America in the end of 2011 and multi-year records from the Washington shoreline documented in 2012 up to 10 times increase in all categories. In summer of 2012 JTMD also reached Hawaii.

Response to the risks associated with JTMD required improved reporting network and advanced numerical modeling. The ADRIFT project, sponsored by the Japan Ministry of the Environment and managed by the North Pacific Marine Science Organization (PICES) brought together international oceanographers with physical, biological and ecological expertise. Numerical experiments with a variety of ocean circulation models, forced by satellite and reanalysis products, allowed to optimize model initial conditions and parameters to successfully reproduce six main “waves” of JTMD on the West Coast of North America in 2012-2016. These model solutions also filled the gaps in sparse at-sea and on-shore observations, described the areas affected by different types of JTMD, and suggested the future fate of remaining floating items. Calibrated using the reports of JTMD boats, the models estimated that about 1,000 boats were originally lost to the tsunami, out of which about 100 boats may be still floating, mainly in the “garbage patch” area.

The analysis of biota that arrived in North America and Hawaii on JTMD discovered large number of species native to the coastal ecosystems east and also south of Japan that survived the journey across the north Pacific and potentially could establish in new eco-regions.

To determine the main “invasion” paths, new mathematical methods were developed and implemented in numerical models that allow to derive the probable trajectory of an object, connecting the known start and end points, and estimate ocean conditions along this trajectory. It was found that the seasonal cycle off the northeastern Honshu is one of the strongest in the North Pacific and it covers the full range of the sea water temperature along the entire West Coast of North America, from Mexico to Alaska. Similarly, the climatology south of Honshu allows warm-water species to colonize JTMD that crossed the Kuroshio Extension and to survive the travel to Hawaii.

Although no new JTMD was produced since 2011, Japanese coastal species continue to arrive in North America and Hawaii. A new NASA-funded project investigates how the introduction of anthropogenic floating debris could change the pelagic ecosystem to make it livable for Asian and American coastal species

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Coastal and Regional Sea Level Rise in Indonesia

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Abstract

Regional and local sea level change impacts coastal nations, deltaic regions, and coastal-oriented industries and rising sea level substantial increases the vulnerability of coastal communities. The GFZ in cooperation with BIG (Badan Informasi Geosparsial) installed and operates three GNSS-controlled stations in Indonesia (Semarang (2012), Kolinamil (harbor of Jakarta, 2013) and Surabaya (2014)). This network establishes a backbone for the 'Coastal and Regional Sea Level Change and Subsidence' (CoRSEA) project.

Lately major cities in Indonesia have experienced significant regional subsidence rates. Jakarta, Indonesia's capital, with 10 Million inhabitants shows a complex and varying subsidence pattern along the coast, which is mainly driven by groundwater extraction and surface load. Also Semarang, a 2 million residence city in north-west Java show strong subsidence rates of partially more than 10cm/yr cm per year, clearly visible in the landscape.

In regions with large rates of land movement, remote sensing techniques become especially valuable. Optical remote sensing shows a highly divergent subsidence behavior in Semarang differing from 0 to more than 10 cm /year within 1qkm.

Since the installation of the GNSS-controlled Tide Gauge station the measured sea level rise has accelerated to a value of >9 cm/yr. But, in consideration of a negative GNSS vertical trend of 10.4cm/year measured directly on top of the tide gauge hut, the "absolute" local sea level decreases with a trend of -2 cm/yr. Altimetry as an independent instrument confirms a local sea level decrease over the past three years measured ~50km offshore of the tide gauge site. Vertical rates in Kolinamil and Surabaya are less than -4mm/yr. However Jakarta with a heterogene subsidence pattern shows areas with subsidence rates larger than 10cm/yr.

In ongoing projects the University of Cologne, BIG/Indonesia and GFZ are studying the coastal sea level hazard by combinig GNSS, tide gauges and altimetry and work towards the understanding of the social science aspects of collective bottom-up adaptation and coping processes of local communities and their risks perceptions.

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Recent Developments in Altimeter Data Assimilation in the Global FOAM System

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FOAM is the Met Office's operational ocean forecasting system. This comprises a range of models from a 1/4 degree global to 1/12 degree regional models and shelf seas models. The system is made up of the ocean model NEMO (Nucleus for European Modelling of the Ocean) and the NEMOVAR assimilation run in 3D-VAR FGAT mode.

Some developments in altimeter assimilation the global FOAM system will be presented. This includes the impact of updating the mean dynamic topography (MDT) from CNES-CLS09 to CNES-CLS13. Use of the newer MDT in altimeter assimilation has resulted in improved consistency with subsurface in situ data, particularly in the tropics. In the assimilation we run an altimeter observation bias correction and with the older MDT the estimated bias matched some of the changes made to MDT with this update. We also plan to test the next CNES-CLS18 MDT when available and results will be shown if it is available in time.

The altimeter data assimilated in the global model has the signal due to high frequency atmospheric variations filtered out. The model, however, is able to respond to atmospheric forcings (if not in a fully realistic way). This inconsistency may result in spurious barotropic sea surface height increments from the data assimilation. This is only an obvious problem at higher latitudes where the wind forcing is strongest. Results from an investigation of methods to improve the handling of this issue will be presented.

A recent development is a 1/12 degree resolution global FOAM configuration. This system is eddy resolving and permitting over a much larger area of the world compared to the 1/4 degree model. Some preliminary assessments of the impact of altimeter assimilation in this configuration will be shown.

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Influence of Eddies and Tropical Cyclone Heat Potential on Intensification Changes of Tropical Cyclones in the North Indian Ocean

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Eddies are known to play a crucial role in the sudden intensification of Tropical Cyclones (TC). In this study, Sea Level Anomaly (SLA) data from satellite altimetry is utilized to investigate the role of eddies on TC intensification in the North Indian Ocean (NIO) basin. 51 TCs in all spanning the years 2001 to 2016 in the NIO have been analysed to understand the impact of Tropical Cyclone Heat Potential (TCHP) vis-a-vis eddies on the NIO TCs. SLA data has been obtained from Archiving Validation and Interpretation of Satellite Data in Oceanography (AVISO), TCHP from National Remote Sensing Centre (NRSC) and cyclone intensity data from Indian Meteorological Department (IMD). From the analysis, it is found that nearly 63% cyclones are affected by Cold Core Eddy (CCE, low TCHP) and only 32% TCs are influenced by Warm Core Eddy (WCE, High TCHP) in the NIO region during the study period. Further, out of the 51 cyclones, 17 TCs were formed during the pre-monsoon season, 28 during the post-monsoon season, and the rest in winter monsoon. Presence of WCE or high TCHP along the cyclone tracks are found to affect TC intensification during the pre-monsoon season. About ~76 % (13) TCs are affected due to the presence of WCE or high TCHP, and only 24% (4) cyclones are affected by CCE (low TCHP) during the study period. In contrast, during post-monsoon season, only 18% TCs are influenced by WCE and nearly 82% (23) TCs by CCE. Investigation of seasonality shows that the pre-monsoon cyclones are more dominated by WCE where as post monsoon cyclones are significantly associated with CCE. WCE are mostly present during the pre-monsoon season in the NIO (both Arabian Sea and Bay of Bengal). Further, TCs in the Bay are less affected by the presence of WCE in post-monsoon seasons, which could possibly be due to the presence of thicker barrier layer in this season

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Altimetry and Ocean Prediction: A GODAE OceanView Perspective

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The purpose of the GODAE OceanView Science Team is to accelerate improvement and exploitation of operational ocean forecast systems. The core GOVST members are scientists that lead the world's major research and development programs for real-time operational ocean forecasts, hindcasts and reanalysis. The acceleration of R&D activity is achieved through the exchange of information and expertise as well as the undertaking of joint assessments. The activities which the GODAE OceanView Science Team focuses on are: 1) assessments of forecast system and component performance combined with component improvements; 2) initiatives aiming to exploit the forecasting systems for greater societal benefit; and 3) evaluations of the dependence of the forecasting systems and societal benefits on the components of the observation system. The GODAE OceanView systems and their societal benefits depend critically on observations, especially satellite altimetry. In this presentation, we will first review current data assimilation practices, the benefit of using altimetry, as well as its limitation. We will then describe how operational systems can take advantage of the latest increase in ocean model resolution as well as more accurate measurements (e.g. SWOT)

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Comparison of Sea Level Time Series from Coastal Altimetry and In-Situ Observations in the Mexican Pacific Coast.

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The performance of coastal altimetry over a regional continental shelf is assessed using sea level data observations by an array of HOBO Level data loggers on eight moorings deployed along the coast of Mexico. Coastal altimetry data from CTOH/X-TRACK in the period between March to December 2008 were compared with corrected mooring data (atmospheric forcing and tides) in order to analyze the coherence between in-situ data and satellite observations. The comparison analysis includes continuous and categorical statistics. The results show a high correlation between coastal altimetry with the in-situ measurements mainly in the high frequency signal associated with coastal processes

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Assessment of Ocean Models Against Altimetric and Gravimetric Measurements from Space

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Satellite altimetry is an important component of the ocean observing systems that measures the total sea level and can improve the skill of ocean models. Satellite gravity mission and ARGO floats measure the part of sea level change due to changes in mass and in volume respectively. The interval 2002-2017 is the longest time span where space-based measurements from altimetry, GRACE and ARGO are simultaneously available.

Although gravimetric data provides valuable constraints on mass driven sea surface height changes, these data are rarely assimilated in ocean simulations and reanalysis runs. The evaluation of ocean model simulations and reanalysis using geodetic data remains challenging, particularly in semi-enclosed ocean basins, due to model assumptions and limitation of satellite-based data in the coastal zone.

We compare in the Mediterranean and Black Sea the sea level change with its mass and steric components. Crucial challenge for the ocean models are the unrealistic boundary conditions at the Gibraltar, Dardanelli and Bosphorus straits and the uncertainties in the air-sea freshwater fluxes and river-runoff. Challenge for the satellite observations is the small dimension of the basins and the land effects in the mass change observed from satellite.

The geodetic data are from the gridded multi-mission altimeter dataset of the ESA Sea Level Climate Change Initiative and from GRACE monthly solutions. We account for Glacial Isostatic Adjustment (GIA) and correct the leakage of land signals using hydrological models. In the Mediterranean Sea we consider two ocean simulations (RMCS, ENEA) and one reanalysis (CMEMS) assimilating satellite altimetry. In the Black Sea we use the BS-CMEMS multi-year reanalysis based on the Nucleus for European Modelling of the Ocean v.3.6 (NEMO) hydrodynamic model. The data assimilation system ingests hydrographic profiles, altimeter sea level anomalies and space-based sea surface temperature. All models use the Boussinesq assumption, which implies conservation of volume rather than mass. As a consequence, the elevation provided by the model is not directly comparable to the altimetric sea level.

We find that in the Mediterranean Sea the models differ mostly in annual amplitude and in the halosteric trend. The best agreement in trend, with 2.2 +/- 0.5 mm/yr in 1993-2016, is found between altimetry and sum of modelled sea level and thermo-steric component. In the Black Sea the trend of thermo-steric component is small over 1993-2016 (0.45 ± 0.01 mm/yr) and the halosteric component is highly inaccurate, due to uncertainties in model freshwater forcing fed in the model and scarcity of the in situ salinity data.

This study suggests that the synergy between altimeter data and model simulations could be used to overcome the errors of mass balances.

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SAR Altimetry Processing on Demand Service for CryoSat-2 and Sentinel-3 at ESA G-POD

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The scope of this presentation is to feature the G-POD SARvatore service to users for the exploitation of CryoSat-2 and Sentinel-3 SAR (Delay-Doppler) Altimetry data, which was designed and developed by the Altimetry Team at ESA-ESRIN EOP-SDR. The G-POD service coined SARvatore (SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation) is a web platform that allows any scientist worldwide to process on-line, on-demand and with a user-selectable configuration CryoSat-2 SAR/SARIN and Sentinel-3 SAR data, from L1A (FBR) data products up to SAR/SARin Level 2 geophysical data products.

The G-POD graphical interface allows users to select a geographical area of interest within the time-frame related to the Cryosat-2 SAR/SARin FBR and Sentinel-3 L1A data products availability in the service catalogue. The processor prototype is versatile, allowing users to customize and to adapt the processing according to their specific requirements by setting a list of configurable options. Pre-defined processing configurations (Ocean, Inland Water, Ice and Sea-Ice) are available for the Sentinel-3 service. After the task submission, users can follow, in real time, the status of the processing. The output data products are generated in standard NetCDF format (using CF Convention), therefore being compatible with the Multi-Mission Radar Altimetry Toolbox (BRAT, http://www.altimetry.info/toolbox/) and typical tools. The following upgrades have been recently introduced: 1) Inclusion of SAR echo and SAR RIP (Range Integrated Power) waveforms in the NetCDF files; 2) Inclusion of STACK Data in the NetCDF files.

Initially, the processing was designed and uniquely optimized for open ocean studies. It was based on the SAMOSA model developed for the Sentinel-3 Ground Segment using CryoSat data (Cotton et al., 2008; Ray et al., 2014). However, since June 2015, a new retracker (SAMOSA+) is offered as a dedicated retracker for coastal zone, inland water and sea-ice/ice-sheet. Following the launch of Sentinel-3, a new flavour of the service has been initiated, exclusively dedicated to the processing of Sentinel-3 mission data products. The scope of this new service is to maximize the exploitation of the Sentinel-3 Surface Topography Mission's data over all surfaces providing user with specific processing options not available in the Ground Segment processing chain and most importantly the data storage and the CPU power are resources offered on-line and scalable. The service is open, free of charge (supported by the ESA SEOM Programme Element) for worldwide scientific applications and available at https://gpod.eo.esa.int/services/CRYOSAT_SAR/.

In the last 3 years: 80 SARvatore, 77 SARINvatore and 15 SARvatore for Sentinel-3 Users were supported with: 178428 CPU hours (that's 20.4 years); 175 TB of CryoSat data storage; 14301/506 processing tasks submitted for SARvatore/SARINvatore; 152 processing tasks submitted for Sentinel-3; 91 TB/ 8 TB of input products processed by SARvatore/SARINvatore tasks; Output produced: 3.3 TB/32 GB; 8.4 TB of input products processed by Sentinel-3 tasks; Output produced: 37 GB.

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Broadview Radar Altimetry Toolbox

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The universal altimetry toolbox BRAT (Broadview Radar Altimetry Toolbox) is a collection of tools and tutorial documents designed to facilitate the processing of radar altimetry data. It can read all previous and current altimetry missions' data. It now incorporates the capability to read the upcoming Sentinel-3 L1 and L2 products. ESA endeavoured to develop and supply this new capability to support the users of the Sentinel-3 mission.

The toolbox is freely available at http://earth.esa.int/brat. The BRAT suite is mostly made of command line tools, of which the BratGUI is the front-end. BRAT can be used in conjunction with MATLAB/IDL (via reading routines) or

C/C++/Python/Fortran via a programming API, allowing users to obtain the desired data, bypassing the data-formatting hassle. BRAT can also be used to simply visualise data quickly or to translate the data into other formats such as NetCDF, ASCII text files, KML (Google Earth) and raster images from the data (JPEG, PNG, etc.).

Several kinds of computations can be done within BRAT, involving both user-defined combinations of data fields that can be saved for posterior use and the BRAT's predefined formulas from oceanographic altimetry. BRAT also includes the Radar Altimeter Tutorial, which contains an extensive introduction to altimetry, showing its applications in different fields. Use cases are also available, with step-by-step examples, covering the toolbox usage in the different contexts.

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GOCE User Toolbox and Tutorial

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The GOCE User Toolbox GUT is a compilation of tools for the utilisation and analysis of GOCE Level 2 products. GUT support applications in Geodesy, Oceanography and Solid Earth Physics. The GUT Tutorial provides information and guidance in how to use the toolbox for a variety of applications. GUT consists of a series of advanced computer routines that carry out the required computations. It may be used on Windows PCs, UNIX/Linux Workstations,and Mac. The toolbox is supported by The GUT Algorithm Description and User Guide and The GUT Install Guide. A set of a-priori data and models are made available as well. Without any doubt the development of the GOCE user toolbox have played a major role in paving the way to successful use of the GOCE data for oceanography.

The GUT version 2.2 was released in April 2014 and beside some bug-fixes it adds the capability for the computation of Simple Bouguer Anomaly (Solid-Earth). During this fall a new GUT version 3 has been released. GUTv3 was further developed through a collaborative effort where the scientific communities participate aiming on an implementation of remaining functionalities facilitating a wider span of research in the fields of Geodesy, Oceanography and Solid earth studies. Accordingly, the GUT version 3 has:

- An attractive and easy to use Graphic User Interface (GUI) for the toolbox,

- Enhance the toolbox with some further software functionalities such as to facilitate the use of gradients,anisotropic diffusive filtering and computation of Bouguer and isostatic gravity anomalies.

- An associated GUT VCM tool for analyzing the GOCE variance covariance matrices.

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Four Years of G-POD SAR Service: A Story of Success

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The CryoSat-2 SARvatore service was made available on ESA-RSS processing platform (G-POD) to all the altimetry user community for the first time on 10 June 2014 accumulating now more than four years of intense exploitation and usage. Further, on 07 June 2015 it was complemented by the analogous service for the CryoSat-2 SARin mode and on 24 June 2017 the SAR service for Sentinel-3 STM mission was activated and made available as well.

The G-POD service coined SARvatore (SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation) is a web platform that allows any user worldwide to process on-line, on-demand and with few clicks SAR data from L1A level up to Level 2 geophysical data products.

This work will describe briefly the concept behind the service, the key points of the service which brought to its success and it will collect all the successful projects and studies which have used the service to achieve their objectives and results in the course of last four years.

The secret of the service success is indeed founded on four essential key points:

- The first key point of the service is the versatility of the processing allowing users from different thematic applications (open ocean, coastal zone, sea-ice, inland water, etc) to identify the processing baseline more tailored to their needs and requirements.

- The second key point of the service is the cloud processing capacity along with the cloud data storage capacity which allow users to get timely the results of the processing and to find in the system's archive all necessary input data and auxiliary data.

- The third key point is the data sharing concept within the user community which has several times identified and reported bugs or errors which helped the service to mature and become more and more robust. Users were also actively functional in the service enhancement proposing evolutions and changes in the implementation.

- The four key point is an easy and handy graphical web interface which allow users to prepare and submit their processing order in few clicks and follow in real time the status.

Finally, the presentation will go through all the evolutions which are planned to take place in the service in the near future and it will explain users how to to deploy their own applications in order to expand the service potentiality

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25 Years of Societal Benefits from Ocean Altimetry

Mission Data

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More than 25 years of ocean altimetry measurements from the highly successful TOPEX/Poseidon and Jason mission series satellites has provided oceanographers and marine operators across the globe with the unprecedented opportunities to use a continuous stream of sea surface height data for operational, commercial, and environmental applications. Beginning in 1992, and extending through the expected mission life of Jason-3 in the next decade, this resource of valuable ocean data has been used to map sea surface height, geostrophic ocean velocity, significant wave height, and wind speed over the global oceans. Altimeter data products are used by hundreds of researchers and operational users over the globe to monitor ocean circulation and improve our understanding of the role of the oceans in climate and weather. Altimeter data has also proved valuable for a suite of practical applications including;

" International ocean forecasting systems,

" Ship routing and sport sailing,

" Precision marine operations: cable-laying, oil production, shipping

" Naval operations,

" Fisheries management,

" Marine mammal habitat monitoring,

" Hurricane forecasting and tracking,

" Debris tracking

The data has been cited in over 5,000 research and popular articles since the launch of TOPEX/Poseidon in 1992, and almost hundreds of scientific users regularly access the global coverage altimeter data. In addition to the scientific and operational uses of the data, the educational community has seized the unique concepts highlighted by these altimeter missions as a resource for teaching ocean science to students from grade school through college

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The Research and User Support (RUS) Service: a New Free Expert Service for Sentinel Data Users

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The RUS Service aims to promote the uptake of Copernicus data, and supports the scaling up of R&D activities with Copernicus data at no cost: to end users. The RUS Service is configured in a scalable cloud environment that offers the possibility to remotely store and process EO data. The RUS Service offers free support to its users via a helpdesk and a team of EO and IT experts who can address any request, coming from beginners to skilled practitioners. Cloud ICT resources are procured with Free and Open-Source Software and Coding Language are tailored to the user needs. The RUS service proposes also on-site training sessions, webinars, and online materials. The RUS Service is offered at no cost and is available for a large spectrum of communities of users and types of institutions.

The objective of this poster is to present the different aspects of the service, including the eligibility of the activities, the type of possible Cloud configurations, software and tools made available, but also the latest evolutions of the offer in the context of the advent of the European DIAS.

This poster illustrates the case of the radar altimetry community that is supported by the RUS service, in particular with Sentinel-3 SRAL data and a combined use of Sentinel-1 C-SAR imager, in every aspect (ICT, thematical and technical aspect, service duration…).

The RUS Service is funded by the EC, managed by ESA, and operated by Communications & Systèmes – Systèmes d'Informations (CS SI) and its partners: Serco SPA, Noveltis, Along-Track, and CS Romania

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Outreaching Hydrology from Space & SWOT

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Hydrology from space is one of the rising remote sensing field of application, with huge issues - environmental, human, economic... - to take into account. Among the issues, there's also the question of explaining how to use those data (from current as well as future satellites) to people not so used to remote sensing, why, how they are made, etc. -- in one word, outreaching hydrology from space. Some portals exist, such as the THEIA portal for land applications through which a number of space data dedicated to land applications (including hydrology) are available (https://www.theia-land.fr/en).

SWOT will be a cornerstone of hydrology from space, and will also be a completely new concept. Some pieces of explanations exists through the CNES space technology training courses (animations available on demand with a license), but more can be done -- and will be, with a major focus on hydrology, but not forgetting the ocean, and the complementarity with currents techniques, including nadir altimetry.

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Contribution of Wide-Swath Altimetry Missions to the Ocean Analysis and Forecasting System in the Iberia-Biscay-Ireland (IBI) Region

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The impact of forthcoming wide-swath altimetry missions to the ocean analysis and forecasting system, based on NEMO (Nucleus for European Modelling of the Ocean) and implemented in the Iberian-Biscay-Ireland (IBI) region, was investigated by means of OSSEs (Observing System Simulation Experiments) performed during the period from January to December 2009. An eddy resolving OGCM (Ocean General Circulation Model) configuration, with horizontal resolution of 1/36° (~3 km), was adopted to obtain the "truth" run representing the "real" state of the ocean in an OSSE approach. Satellite altimetry and in situ pseudo observations are extracted from this simulation. Those synthetic observations were assimilated into a different eddy resolving OGCM, implemented in the IBI region with a horizontal resolution of 1/12° (~7 km).

OSSEs were carried out using different observing system configurations, considering both conventional altimeters (Jason2, Cryosat2 and Sentinel3) and a constellation of wide-swath altimeters, and investigating the sensitivity of the system to the instrumental error of wide-swath altimetry data. In this study wide-swath altimetry data were obtained using the SWOT simulator (Gaultier et al., 2016a), provided by JPL (Jet Propulsion Laboratory). The same synthetic observations of SST, T and S profiles were considered in all the experiments. The OSSEs performances were evaluated by comparing the results of each experiment with the "truth" data. We found wide-swath altimetry has a major impact for the ocean analyses. A constellation of two wide-swath altimeters allow reducing the variance of error in ocean analysis by more than 60 % in the open ocean.

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Improved Retrieval of Titan Surface Topography from the Delay-Doppler Algorithm Applied to Cassini Radar Altimeter Data

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During its 13 years of activity the Cassini RADAR altimeter acquired 40 elevation profiles of Titan, Saturn's largest moon. Due to flyby geometry the spacecraft operated at various altitudes, providing broad-scale surface topography measurements. We applied the delay/Doppler algorithm to the radar altimeter data products, adapting it to the specific orbital geometry conditions of the Cassini spacecraft. We present results obtained for the observations of different terrain units, such as dunes, hummocks and mountains. We show that the coherent processing combined with multi-look of Doppler filters, can permit up to tenfold improvement of the along-track resolution and a remarkable radiometric enhancement respect to the standard products

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New Altimetry Missions to Observe the Cryosphere

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CryoSat-2 was successfully launched from Baikonur Cosmodrome in April 2010. Since then, it has continuously monitored the ice thickness evolution over the Polar Regions and it has provided valuable information on the Earth's Cryosphere and also oceans. There is a continuous international user need to have a long term climate data record of land and marine ice sheet retrievals, which are drivers for climate changes at a global level.

With an emphasis on the space segment design and implementation, this paper discusses the basic requirements at an early stage and describes a concept for future altimetry missions to observe the cryosphere which would allow a further improved understanding of the global cryosphere and its interactions with the planet's atmosphere and hydrosphere. The article highlights the concept to further prolong the existing data records from past and present missions in support of continued investigation of long-term climate trends and, in addition, presents means to take benefits from any possible technical innovations that may allow improving the geometric, radiometric and temporal resolutions. Likewise, the spatial and temporal resolution has also to be supported by a careful choice of the orbit and the mission concept for future altimetry missions observing the Cryosphere. In particular, the following aspects will be addressed: an assessment on different overall concepts with varied orbits and considering also satellite formations and combination with existing missions in the Copernicus frame. Future satellites needs and capabilities in order to embark future instrument evolutions will be presented

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Data-Driven and Learning-Based Approaches for the Spatio-Temporal Interpolation of SLA Fields from Current and Future Satellite-Derived Altimeter Data

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Theme : big data, deep learning and analog strategies

The spatio-temporal interpolation of sea surface tracer fields from satellite-derived altimeter data generally relies on model-based schemes, the most popular ones being optimal interpolation schemes which exploit space-time covariance models. The ever increasing availability of in situ, remote sensing and simulation data make more and more appealing data-driven alternatives, which may learn more complex representations of the underlying dynamics with a view to improving the reconstruction of fine-scale processes.

We will first review three categories of data-driven schemes, namely patch-based super-resolution models [Fablet et al., 2018], analog assimilation models [Lguensat et al., 2017] and neural-network-based assimilation models [Fablet et al., 2017]. We give more emphasis to the last two ones, which appear more generic. They are both stated within a Kalman-based assimilation framework (namely the ensemble Kalman filter and smoother). They differ in the considered data-driven dynamical model. The analog assimilation models exploit analog forecasting operators (especially locally-linear analog operators) under the assumption that analog states share similar dynamics. By contrast, neural network (NN) architectures provide explicit representations of the dynamical operator. We focus on residual and convolutional architectures which may be interpreted as numerical integration schemes of differential equations (Fablet et al., 2017). For such data-driven and learning-based schemes, the representativeness of the training data are critical issues. When dealing with high-dimensional geophysical dynamics, the curse of dimensionality may make poorly relevant their straightforward application to the entire space-time domain of interest. We then discuss and introduce multiscale patch-level representation as means to overcome these issues.

We present numerical experiments for the spatio-temporal interpolation of SLA fields from satellite-derived altimeter data using OSSE (Observing System Simulation Experiment) settings. We consider two types of satellite-derived altimeter data, along-track nadir data and upcoming wide-swath SWOT mission.

As case-study region, we consider a region in the western Mediterranean sea with rich mesoscale and submesoscale dynamics. ROMS numerical simulations with a 0.02°x0.02° resolution over 5 years are used to implement the considered OSSE. The first 4 years are used for training. We apply the proposed interpolation schemes to the last one to evaluate their reconstruction performance. Overall, our results support a significant potential improvement for horizontal scales ranging from 20km to 100km with a gain of 42% (12%) in terms of SLA RMSE (correlation) with respect to the optimal Interpolation. Our results also suggest possible additional improvement from the joint assimilation of SWOT and along-track nadir observations.

We will further discuss the pros and cons of data-driven and learning-based schemes for the reconstruction of SLA fields, especially future research directions to bridge model-driven and data-driven reconstruction schemes.

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Experiment at the International Space Station: a Microwave Radar With Scanning Fan Beam Antenna at Nadir Probing

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Advantage of the measurements at the small incidence angles is explained by the fact that characteristics of the backscattered radar signal is directly determined by the parameters of sea waves, because a microwave backscattering is quasi-speqular. Therefore, it is possible to retrieve parameters of large-scale waves by remote sensing methods.

Altimeter is the most known the example of such radar. Altimeters provide information on SWH along the ground track of satellite. Specific motion of the satellite implies that may be obtained only section of the processes occurring on the ocean surface. Since the distance between neighboring tracks may be more than one hundred kilometers, the information proves to be rather fragmentary and insufficient for operational needs. Resolution of altimeter is approximately 5 km, therefore radar can measure in the coastal area and inland waters.

Dual-frequency precipitation radar (DPR), developed by JAXA, measures at the small incidence angles (+/- 18 degrees) and has the wide swath (245 km in Ku-band and 120 km in Ka-band). Developed algorithm permits to retrieve the mean square slopes (mss) of large-scale waves in swath with resolution 5 km. Due to this resolution the DPR may measure in coastal area and inland waters too.

In our previous papers the concept of radar with fan beam antenna was suggested. Concept of new radar is based on the advanced theoretical scattering model which was developed in our group. First experiments have confirmed the theoretical conclusions.

This concept was supported by the Russian space agency and a new radar will be developed and tested during experiment at the International Space Station (Russian segment). New radar will have a fan antenna (~ 1.5 x 30 degrees) and a footprint will be oriented along the direction of flight.

To obtain a wide swath it is suggested to scan the antenna footprint across the direction of flight. As a result, we have a wide swath (incidence angles are approximately +/-13 and a width of swath is approximately 160 km at 400 km altitude) with a spatial resolution is about 10 x 10 km.

During space experiment will be tested two operation modes: 1) mss of large-scale sea waves and 2) mss and SWH of sea waves. Wind speed retrieval algorithm will be tested in both operation modes.

In result we will have a few image of sea surface: 1) a radar image (radar cross sections) 2) a mss field in two directions 3) a SWH field and 4) wind speed field. It is powerful instrument for investigation of sea surface processes. Knowledge about mss in two directions can permit to retrieve the direction of wave propagation.

The project began to be implemented in 2018. This year it is planned to develop a technical project. The installation of the new radar at the International Space Station and the start of experiments is scheduled for 2022.

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On the Assimilation of High-Resolution Wide-Swath Altimetric Data

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The assimilation of historical, along-track altimetry has received considerable attention since TOPEX/Poseidon in 1992 because it allows the elaboration of complete, gridded maps of ocean surface topography, which are used for scientific and operational purposes. Data assimilation methodologies are now challenged by two-dimensional, high-resolution satellite observations such as optical images or wide-swath altimetry. One specific issue, addressed in this work, resides in the presence of spatially correlated noise in the data, and in that this correlated noise often comes on top of some spatially uncorrelated errors.

Data assimilation algorithms require the parameterization of the observation error covariance matrix, and most of them are coded under the hypothesis that this matrix is diagonal, what makes them suboptimal or ineffective. Our group has developed a methodology to account for observation error correlations in those algorithms, while preserving their original formulation. The methodology is based on the introduction of spatial derivatives of observations. But the implementation meets two obstacles: first, the derivatives of model's outputs and observations must be computed on identical grids, and second, the direct calculation of derivatives is not possible due to the uncorrelated noise superposed to the correlated one.

We will present our recent advances on the theoretical and methodological aspects of data assimilation in presence of two-dimensional satellite observations with spatially correlated errors, with a prospective application to the future Surface Water and Ocean Topography (SWOT) wide-swath altimetry mission. The first obstacle mentioned above is solved by extending the state vector with its observed part, obtained using the SWOT simulator for ocean science (https://github.com/SWOTsimulator). This makes the calculation of derivatives strictly identical between the SWOT data and model's data. The second obstacle is overcome by the application of an image denoising technique specifically designed for SWOT data. This approach allows the use of localization techniques classical in data assimilation, what makes it applicable for high-dimensional systems. Illustrations will be shown based on outputs from the NATL60 simulation (NEMO 1/60 degree, North Atlantic) and an Ensemble Kalman Filter for data assimilation.

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Ku/Ka Radar Altimeter for a Polar Ice and Snow Topography Mission

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This abstract presents the last advances of Thales Alenia Space to support ESA in the definition of a radar altimeter suitable for a potential ice and snow topography mission. The first objective of this work is to define the continuity of the Cryosat-2/Siral-2 mission which is currently operating in orbit. The Siral-2 instrument is a nadir-looking Ku-Band radar altimeter with interferometric capability.and supports Low Resolution Mode (LRM), SAR Closed Burst (CB) and SAR Interferometric (SARIn) CB modes shared out among different surface types.

The main evolution on the radar instrument is the addition of Ka-Band with the aim to retrieve the snow depth on sea ice surfaces and to characterize better the penetration effect into the snowpack over land ice.

For this new instrument, the LRM mode is intended to be dropped since it will be substituted by the SAR CB mode over open ocean and coastal zones to improve performances. An enhanced version of the SARIn CB mode, dedicated to Land Ice and Glaciers surfaces, is also proposed by providing 4 times as many measurement bursts as Cryosat-2 to improve height and phase accuracies over these surfaces. At last, the SARIn interleaved mode operated at a PRF of 18 kHz is proposed over sea ice surfaces in order to improve the azimuth resolution down to the fully-focused SAR performance and to provide the angle of arrival of sea ice freeboards. Ka-Band pulses are added on top of the Ku-Band chronograms for all the modes without affecting the original Ku-Band performances. It is foreseen to transmit Ku- and Ka-Band pulses simultaneously or in an alternate way depending of the radar mode: Closed-Burst chronograms accept both ways of transmission whereas the SARIn Interleaved chronogram is only compatible with simultaneous transmission in the two bands due to the short time slot given by the Pulse Repetition Interval.

Another main evolution is the use of Ku/Ka chirps with 500-MHz bandwidth in order to maximize the range resolution of the altimeter and the accuracy of snow depth retrieval. In addition, the instrument will provide improved tracking performances by tracking Points of Closest Approach (POCAs) on high slopes (target : 5°) and by acquiring echoes generated by icebergs with a high freeboard (target : 75 m). At last, a trade-off on the Ka-Band antenna footprint will be performed between the maximization of the antenna gain to optimise acquisition of nadir echoes and the enlargement of the across-track aperture to optimise acquisition of off-nadir points (e.g. POCAs) in Ku and Ka-Band. The optimal architecture which has been designed to implement these new features will also be presented with the associated performances.

As a conclusion, the radar altimeter for future ice and snow topography missions achieves significant scientific progress wrt Siral-2 while it includes the most up to date technologies releasing thus a highly integrated design.

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Sentinel-3 Topography Mission Payload

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Initiated in 2008 for phase B, Thales Alenia Space is about to provide its second satellite S3B in orbit in April 2018. S3A satellite has been launched 2016 February 16th and has now provided continuously more than two years of data.

Thales Alenia Space has been in charge of the definition, procurement and integration and test on the satellite of the suite of instruments composing the topography Payload suite. In parallel of the development of the payload, the system simulator and the IPF prototype processors have been defined and developed with CLS opening the way to the operational delivery of the Topography Products flawlessly since S3A launch.

The paper will present the topography package payload of Sentinel-3 comprising the Sar Radar Altimeter (SRAL) developed by Thales Alenia Space, the MicroWave Radiometer (MWR) developed by Airbus DS Spain, GPS receiver developed by Ruag Space and Laser Retro-Reflector. For Sentinel- 3 A and B models, the payload also comprises a DORIS instrument provided by CNES.

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Swath Altimetry for Operational Oceanography

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Ocean nadir altimeters are limited to the measurement of the sea surface height (SSH) at the sub-satellite point. The spatial / temporal sampling of the ocean is therefore limited for a single mission. Moreover, the across-track component of the SSH can only be assessed at the orbit cross-overs, which is a limitation for the derivation of the current fields. Swath altimeters improve the spatial/temporal sampling of the ocean, the across-track component of the SSH is available over a typical swath of 100 km centered on nadir, and the spatial resolution -the pixels size over ocean- is improved with respect to nadir altimeters. The SWOT mission embarking the KaRIn (Ka-band) swath altimeter will demonstrate the technique at the technology level and at the science level say by 2022.

Alternative concepts focused on operational oceanography requirements have been proposed in the past by Thales Alenia Space. They rely on simpler antenna subsystem than for SWOT to moderate the complexity and cost of the mission. Those concept studies were funded internally by Thales Alenia Space and also supported by CNES and ESA contracts.

Thales Alenia Space is also developing -under CNES contract- the Radio Frequency Unit of the KaRIn radar, which –together with its altimeter product line- provides technological European heritage for a future operational mission.

Thales Alenia Space currently works at the definition of an operational swath altimetry mission for Copernicus NG, in the frame of an ESA contract, with CNES support for the user requirements identification. The paper will present an overview of the findings and concepts of swath altimeters for operational oceanography, based on past and on-going contracts with CNES and ESA.

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Design Status of the Ka-Band Scanning Doppler Scatterometer for the SKIM Mission

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The SKIM "Sea surface KInematics Multiscale monitoring" mission has been selected for phase A study in the frame of ESA Earth Explorer 9 Fast-Track mission. Thales Alenia Space is the instrument provider for this mission having developed relevant technology heritage from past missions (SWIM instrument for the CFOSAT mission and KaRIn RF unit for the SWOT mission).

Because the ocean surface is the interface between ocean, atmosphere and land, the ocean currents play an important role in defining the fluxes of heat, momentum, carbon, water, etc. between Earth System components. The ocean surface velocity combines surface currents (mainly driven by winds, density gradients, and tides), with wave-induced drift, known as Stokes drift. This total velocity transports surface heat, salt and everything that is in the upper ocean, natural or man-made, including microplastics. While largely improving over the passed satellite era, there is still a false sense of knowledge on ocean currents and waves. Satellite altimeters have been around for over 20 years, but along-track sea level anomaly and significant wave height are not enough to characterize the multi-scale motions of the oceans.

This is particularly true in the tropics where geostrophy explains a small fraction of surface currents and does not give access to the very important divergence and upwelling, the structure of which is poorly known. This is also true at the ice edge. The Arctic is going through a major regime change, with a widening Marginal Ice Zone (MIZ). A strong coupling is expected at the ice edge between ocean currents, ice, waves and atmosphere that is very difficult to observe today. It is urgent to add kinematic variables (surface current, ice drift, waves) that can be resolved at the relevant scales, smaller than those at which dynamic variables (sea level, wind stress) are available today.

The SKaR radar from Thales Alenia Space to be flown on SKIM measures total ocean surface velocity vector (primary goal), using a Doppler technique that is more direct than altimetry for accessing surface currents. The measurements will also provide ocean wave spectra (Doppler and amplitude) which are needed in the retrieval of ocean currents. An accurate current measurement require a complete measurement of the sea sate at different scale (from shortest wave components) to separate wave-current interactions. Therefore, SKIM combines in a single Ka-band instrument an accurate state of the art Nadir looking altimeter (sea level, wave height, ice freeboard, …) and a novel wave+current spectrometer using 5 to 7 rotating beams around Nadir at 6° and 12° of incidence (measurement of full surface slope spectrum, Stokes drift, current and wind vectors).

At the time of the "25 years of progress in radar altimetry" symposium, the Preliminary Concept Review will be held. Therefore, instrument architectural trade-offs results, performances analysis and error budgets will be reported, system drivers affecting the technical and operational complexity/feasibility of the instrument will be presented as well as the instrument baseline and its technology maturity

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Technical Challenges and Status of the Ka-Band Interferometric Radio-Frequence Unit for the SWOT Mission

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The SWOT -Surface Water and Ocean Topography- mission developed in cooperation between JPL/NASA, CNES, CSA and UKSA is a breakthrough in altimetry with an enhanced side looking radar, KaRIn, combining Doppler processing and interferometry.

THALES ALENIA SPACE is developing the RFU (Radio Frequency Unit) of KaRIn under CNES contract, the complete KaRIn radar being developed by JPL. The program is now in phase CD with the validation of the RFU engineering model and the manufacturing of the RFU proto-flight model. The radar operates at Ka band. The Radio Frequency Unit is in charge of main analogic functions : the clocks and locals oscillators supply, the low level and accurate radar scheduling, the pulse emission, the echoes reception and the routing of Ka-band signals. While the frequency of 35.75 GHz has the advantage of high interferometric sensitivity, challenges exist in the RFU for keeping the inter-channel differential phase noise at the lowest possible level and to ensure differential phase stability.

State-of-the-art technologies and design are used to meet the stringent performance requirements in phase noise and differential phase stability. We will show how the requirements are met based on design and on internal calibration of the RFU. The calibration scheme will be briefly introduced. A focus on the verification methodology and the developed metrology will be shown. Final results obtained on the electrical model of the Radio-Frequency Unit of the KaRIn instrument will be presented.

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Sentinel-6 Level-1 Poseidon-4 Ground Processor Prototype Architecture and Processing Modes

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Sentinel-6 (Jason-CS) is an operational oceanography programme of two satellites that will ensure continuity to the Jason series of operational missions. The mission is being developed by a multi Agency partnership consisting of ESA, EUMETSAT, NOAA, CNES and NASA-JPL. ESA is responsible for the Sentinel-6 (Jason-CS) Space Segment development along with Airbus GmbH as a prime contractor.

The main payload of the Sentinel-6 satellite is the Poseidon-4 radar altimeter, an evolution from the altimeters on-board the Jason satellites. Poseidon-4 also inherits the Synthetic Aperture Radar (SAR) High Resolution Altimeter mode from CryoSat-2 SIRAL and Sentinel-3 SRAL, with a technological evolution characterised by:

- Improved radio frequency hardware and an on-board digital architecture (matched filter digital operation instead of analogue-based de-ramping).

- Interleaved Ku-band mode operation: near continuous transmission of Ku-band pulses. It allows the simultaneous operation of the low resolution mode (LR or LRM) and high resolution (HR or SAR).

- On-board processing, range migration correction (RMC), is performed on the SAR Raw data to reduce the amount of data to download, with the same rate, thus producing the SAR RMC data.

- A calibration pulse is included in the tracking cycle to monitor instrumental variations around the orbit.

isardSAT is responsible for the development of the Level-1 Ground Prototype Processor (GPP) for the Sentinel-6 Poseidon-4. This prototype processes all the chains starting from the Instrument Source Packets (ISPs, also known as Level-0 data), and producing Level-1A and Level-1B-S (only for HR processing) and Level-1B (all modes). The prototype has been verified using simulated data generated by the ESA Sentinel-6 mission performance simulator provided by ESA and also using in-orbit CryoSat adapted data.

The processing chains of the GPP are divided into the scientific modes, Low Resolution (LR), High Resolution (HR), Low Resolution Over-sampled (LR-OS), Low Resolution from RMC (LR-RMC) that produce geophysical results and the calibration modes, CAL1 LRM, CAL1 SAR and CAL Pulse, that produce calibration results for the scientific modes. Besides, the HR and LR-OS processing chains can ingest two different Level-0 data: SAR Raw data and RMC data.

This presentation will review the Level-1 GPP in terms of its architecture and the different processing modes available, explaining the differences between them and evaluating the use case for each mode: some modes will be used depending on the surface type (e.g. HR from SAR / HR from RMC), other modes will be used always (e.g. LR), some modes can coexist with other modes, thus allowing cross-validation of the different modes (e.g. LR and HR, HR from SAR and HR from RMC).

The Level-1 output products generated by each processing mode will be described, outlining their main parameters and their potential utility for the scientific community. We will also present the different auxiliary files, their sources and use.

Finally, the performance on the geophysical results and the software requirements, such as the run-time performance, for each processing chain will be presented and compared

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Surface Water Ocean Topography Mission Retrievals in the Ice-Covered Polar Oceans

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Satellite radar altimetry has proven to be a valuable tool for remote sensing of the polar oceans, with techniques for estimating sea ice thickness and sea surface height in the ice-covered ocean advancing to the point of becoming routine, if not operational, products. Scheduled for launch in 2021, the Surface Water and Ocean Topography mission (SWOT) payload, the Ka-band Radar Interferometer (KaRIn), will employ radar interferometry to estimate an ~120km across-track swath of elevation. In the polar oceans, SWOT offers the potential to provide high resolution two-dimensional maps of sea level and sea ice elevation, to derive instantaneous 2-D ocean currents and a detailed picture of the sea ice thickness distribution. Here, we present results from preliminary investigations into the KaRIn retrieval performance in the ice-covered oceans. First, we utilise the available near-incidence Ka-band data to study the range of possible radar backscatter profiles. Second, the range of possible radar backscatter profiles will be applied in the SWOT mission simulator to produce synthetic data and evaluate the expected measurement capability.

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High Temporal SSH Measurements Using Wideband Ku-band Signals of Opportunity

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Satellite altimeters, which have played a significant role in mapping the variability of the Earth's open ocean, have known limitations in coastal oceans resulting from land contamination and rapid variations due to tides and atmospheric effects. Coastal zones, currently home to a large fraction of the world's population, are under serious threat from coastal erosions, storm surges, and deadly tsunamis. Additionally, conventional satellite altimeters typically have long temporal resolution (repeat time) of greater than 10 days, which is thus far inadequate to resolve temporal and spatial variability in coastal oceans.

For this reason, there is a need to improve the capability of Sea Surface Height (SSH) observations in near-coastal areas and increase temporal resolution of observations. One promising technology is the use of Signals of Opportunity (SoOps). SoOps are communication satellite transmissions that are reutilized as illumination sources in a bistatic radar configuration. A number of transmissions from direct broadcast satellites (DBS) in geostationary orbit occupy very large bandwidth (400-500 MHz) allocations in the Ku- and Ka- spectrum bands. Theoretically, SSH can be estimated by measuring the reflected path delay of these signals with very high precision (on the order of 4-5~cm) due to the large bandwidth and high signal- to-noise ratio [1]. Since SoOp technology requires only receiver technology to be placed in orbit, small satellite platforms can be used, enabling a constellation to be designed that achieves the desired spatial-temporal resolutions. Because of the random sampling and high temporal resolution from SoOp receivers, this technology is complementary to synthetic aperture and wide swath instruments.

We plan to present development of error models from spaceborne mission that is based on the models developed from Platform Harvest experiment that was conducted in 2017. Furthermore, coverage analysis of constellations of receivers utilizing all the available Ku-band signals will be shown to quantify possible temporal resolution that can be achieved from a constellation of

SoOp receivers. Finally, potential scientific application of Ku-band constellations will be discussed

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SWOT in the Tropics: Designing a Joint In Situ Experiment with SWOT during the Fast-Sampling Phase to Sample Small-Scale Dynamics around New-Caledonia

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The oceanic circulation around New Caledonia involves a substantial mesoscale eddy field, associated with submesoscale features, as well as substantial internal tides generated by the steep bathymetry of the region. The future SWOT satellite will fly next to New Caledonia during the Cal/Val fast-sampling cycle and will provide an unprecedented opportunity to characterize the small-scale dynamics down to 20 km in this region.

The analysis of former observing dataset have demonstrated the capacity of gliders to sample and capture internal waves as well as submesocale structure down to 1000m around New Caledonia. Structure functions applied on shipboard velocity measurements have also shown that submesoscale features probably dominate surface layer motions whereas wave-like features are substantial in the ocean interior. We are also analyzing along-track data from SARAL-Altika and Sentinel 3 to capture these dynamics from sea level observations.

In order to understand the complex content of the observed small-scale sea surface height as well as the impact of the errors linked to the subsampling of scales shorter than 20 km, we suggest that similar in situ observing systems could be deployed from the oceanographic center of Noumea during the SWOT phase sampling state. A combination of gliders and one high-resolution mooring is proposed to accurately sample the vertical structure of internal waves and their horizontal propagation. These observing systems will also serve to diagnose submesocale fronts and filaments.

This in situ characterization of small-scale ocean dynamics will be compared with the SWOT signal during the fast-sampling phase to answer two main questions: What would be the bidimensional imprint of internal waves and submesoscale features on the SWOT signal (physical signal and noise level)? Would the SWOT sea-level signal be exploitable to infer information on vertical velocities?

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Transition of SAR Interferometric Altimetry from R&D to Operations

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Over the course of the last two 25 years satellite radar altimetry has been transformed from a research endeavour into an operational enterprise. European research and technology contributions to the series of ERS-1/2, TOPEX-Poseidon, Jason, Envisat, CryoSat, and AltiKa altimeters have paved the way for the latest series of operational topography missions. Today Copernicus Sentinel-3 and Sentinel-6 Synthetic Aperture Radar (SAR) altimeter-based missions offer the capability to deliver products and services for (amongst others) marine environment monitoring, met-ocean forecasting, ice sheet ECV, sea level ECV, river and lake levels, and sea-ice forecasting.

Since the mid 2000s, a step change has taken place with the development of the Synthetic Aperture Radar Interferometric ALtimeter (SIRAL) instrumentation developed for CryoSat-1 and -2. Technical heritage from these missions has been progressively integrated into the ongoing Sentinel-3 SRAL mission and the Sentinel-6 partnership mission currently in development. Meanwhile, recent studies have proven that the full power of this novel Delay-Doppler technology is not yet fully exploited. Efforts to further harness the full SAR interferometric capability over regions of polar ice sheet topography are yielding new benefits, in precisely the regions where traditional pulse-width limited altimeters have been challenged, offering improvements in temporal sampling density. Similarly, new methods of fully-focussed SAR (ff-SAR) processing are being progressively integrated in the ground data processing to overcome the same limitations of traditional for ocean sea ice and hydrology applications of altimetry, offering sensitivity to elevation signals at much smaller space scales.

Over ice sheets, ice caps and glaciers, the swath processing technique using the interferometric mode of CryoSat-2 improves upon the traditional maps of ice-sheet elevation and elevation change (at 3–10 km spatial resolution and seasonal to monthly temporal resolution). Swath processing yields broad (~ 5 km-wide) swaths of surface elevation with fine (500 m) spatial resolution from each satellite pass, providing a dramatic improvement in the capability of satellite altimetry for glaciology and mapping and monitoring the impact of ice sheet change on sea level. Each swath of elevation data contain up to two orders of magnitude more surface elevation measurements than standard altimeter products. Resulting swath elevations allow more dense, statistically robust time series of elevation change to be formed with temporal resolution of a factor 5 higher than using traditional processing.

Recent investigations of the potential of fully-focussed SAR (ff-SAR) along-track processing demonstrate that this approach leads to a significant increase in the effective number of looks with respect to the delay/Doppler processing, resulting in more robust geophysical parameter estimation. Despite the asymmetry of the ff-SAR altimeter footprint, the technique is demonstrably useful for rivers and lakes, sea ice lead detection, coastal ocean altimetry applications along complex coastlines.

With ESA preparatory activities ongoing for a Copernicus High Priority Candidate polar ice and snow topography mission, maturation of swath processing of SAR interferometry and ff-SAR altimetry data offers a timely possibility for incorporation of these latest developments in the design of this mission concept. These recent developments in data processing offer exciting opportunities and an optimistic future for operational polar-orbiting altimetry, and will yield significant benefits in the further development of applications and operational service development using altimetry data.

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S6 P4 GPP: The Sentinel-6 Poseidon-4 Ground Processor Prototype. Performance Validation.

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Sentinel-6 is an operational oceanography programme of two satellites that will ensure continuity to the Jason series of operational missions. The mission is being developed by a multi-Agency partnership consisting of ESA, EUMETSAT, NOAA, CNES and NASA-JPL. ESA is responsible for the Sentinel-6 Space Segment development along with Astrium GmbH as a prime contractor.

The main payload of the Sentinel-6 satellite is the Poseidon-4 radar altimeter, an evolution from the altimeters on-board the Jason satellites. Poseidon-4 also inherits the Synthetic Aperture Radar (SAR) High Resolution Altimeter mode from CryoSat-2 SIRAL and Sentinel-3 SRAL, with a technological evolution characterized by:

- Improved radio frequency hardware and an on-board digital architecture (matched filter digital operation instead of analog-based de-ramping)
- Interleaved Ku-band mode operation: near continuous transmission of Ku-band pulses. It allows the simultaneous operation of the low resolution mode (LR or LRM) and high resolution (HR or SAR).
- On-board processing, range migration correction (RMC), is performed to reduce the amount of data to download.
- A calibration pulse is included in the tracking cycle to monitor instrumental variations around the orbit.

This new configuration of the Poseidon-4 instrument opens a new paradigm in the capabilities offered by the Sentinel-6 radar altimeter. In order to do so, the specificities of this new instrument have to be carefully considered in order to re-adapt the Delay-Doppler Processing algorithms. isardSAT is responsible for the development of the L1 Ground Processor Prototype (GPP) for the Poseidon-4 under ESTEC/ESA contract. This prototype processes all the chains starting from the Instrument Source Packets, and producing L1, L1B-S (only for HR processing) and Level 1B (both calibrated LR and HR data processing). This processor includes a lot of new features thanks to the experience gained with CryoSat-2 data as well as to the many studies performed during the course of the Sentinel-6 GPP project. The development of the GPP has been carried out exploiting simulated data produced by ESTEC Sentinel-6 mission performance simulator.

This presentation will provide a review of the architectural and algorithmical implementation of the GPP, stressing how this processing chain has been adapted to the new characteristics of the Poseidon-4 instrument and the related implications. The operation of the GPP will be demonstrated with new simulated data (considering different scenario conditions), up to date with the last instrumental configuration. A validation of the GPP data will be included, based on the geophysical retrievals processor implemented by isardSAT in the frame of the Sentinel-6 GPP project. This processor integrates a fully analytical HR ocean retracker based on Ray et al. 2015 model and adapted to the new Sentinel-6 Poseidon-4 characteristics. Preliminary results on the innovative Fully Focused SAR (FFS) processor implementation for Sentinel-6 will be potentially evaluated.

References:

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The Altimeter Product Suite for Sentinel-6/Jason-CS Mission

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The Sentinel-6 (Jason-CS) mission will follow TOPEX and the Jason-series of "reference altimeter missions". But it is in many ways a totally new type of mission, a different platform (similar to CryoSat) and a different altimeter (dissimilar from any of the previous altimeters). Not only will it be the first Synthetic Aperture Radar (SAR) altimeter used on one of the reference missions, it will also be the first altimeter that operates in a continuous high-rate pulse mode, 100% of the time. This particular operating mode allows simultaneous production of Low

Resolution (LR) mode measurements on-board as well as the processing of SAR echoes (High Resolution, HR, processing) on-ground. Both types of measurements will be provided in (separate) Sentinel-6 altimeter data products.

Sentinel-6 will bring some unique opportunities for cross-calibrating and cross-validating LR and HR altimetry, housed on the same platform, working from the same altimeter echoes, just using different processing techniques. Also, it will be the first time that we will be able to fully process on-ground 100% of the echoes that would otherwise be averaged on-board. This presentation will show how this is reflected in the Sentinel-6 products, how these compare with the products of the Jason-series and of Sentinel-3 and how continuity is ensured. Particular emphasis will be on highlighting the Level 1A (L1A) and Level 1B (L1B) product content.

Level 1 products will be made available containing all the individual echoes in the time domain (L1A) or the measurement data and waveforms without geophysical corrections (L1B). A L1B-S product (with the individual waveforms stacked and geo-located such as is available for Sentinel-3) can be derived from the L1A after performing Delay Doppler processing. Although L1B-S is not part of the product line, a tool will be provided to the users so that they can process L1A to L1B-S.

Level 2 (L2) products will contain the geophysical measurements of sea level, wind speed, and significant wave height, at 20-Hz and 1-Hz, from both LRM and SAR altimetry. They will also contain an appropriate set of geophysical corrections, outlined in this presentation, aimed at providing sea level measurements at the cutting edge of what is feasible. In numerous cases alternatives are provided to support various applications and error assessment. The L2 products can be easily aligned with the L1B products (and vice versa) in order to combine waveforms and geophysical corrections and retrievals.

Around the time of the Conference, test datasets will be made available. Users will be invited to provide feedback on the content, applicability, and format. The presentation will show highlight some of these.

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